Co-conception des processus d'usinage et des configurations cinématiques d'un système de production reconfigurable

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Co-conception des processus d'usinage et des configurations cinématiques d'un système de production reconfigurable

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Avant Propos

Ce mémoire de thèse représente une synthèse de mes activités de recherche menées depuis Septembre 2006.

Ces activités ont été effectuées sous les statuts :

- d'allocataire d'une bourse (*Higher Education Commision* (HEC) Pakistan) de Septembre 2006 à Septembre 2009. Cette bourse a été obtenue suite à un concours national, pour le développement des universités pakistanaises (étant actuellement en poste à la *National University of Sciences and Technologies* de Rawalpindi)
- d'A.T.E.R. à Arts et Métiers ParisTech Metz avec des enseignements en informatique (algorithmique) et mathématiques (méthodes numériques) de Septembre 2009 à ce jour.

Ces travaux s'inscrivent dans la problématique de conception des systèmes de production, ils visent plus particulièrement à répondre à la question : « Comment optimiser la conception du processus d'usinage et du système de production reconfigurable en tenant compte des interactions entre le processus et les ressources, et des contraintes technologiques imposées par les pièces à fabriquer ? » via une proposition de co-exploration des espaces de solutions processus d'usinage et configurations cinématiques du système de production.

Etant donné l'aspect international de cette thèse et suite à la décision DG2009-46 du 1er Octobre 2009, le Directeur Général d'Arts et Métiers ParisTech a autorisé la rédaction de ce mémoire en deux langues : anglaise et française. De ce fait, ce document se divise en deux parties : un résumé étendu en français sans figure et le descriptif des travaux en anglais avec les figures.

Foreword

This thesis represents a summary of my research activities performed since September, 2006.

These activities were performed under the status:

- Recipient of a scholarship (*Higher Education Commision* (HEC), Pakistan) from September 2006 to September 2009. This scholarship was obtained after a national level examination and selection process for the development of universities and promotion of higher education in Pakistan (serving in *National University of Sciences and Technologies* at Rawalpindi)
- Performing as A.T.E.R. at Arts et Métiers ParisTech Metz and teaching the subjects of computer sciences (algorithms) and mathematics (numerical methods) from September 2009 to date.

This work is done in the domain of the design of production system; it attempts in particular to respond to the question “How to optimize the design of the manufacturing processes and reconfigurable manufacturing system while taking into account the interactions between the processes and resources, the technological constraints imposed by the part to be manufactured?, via a proposal for the co-exploration of the solution space characterized by machining processes and kinematics of the production system.

While taking into account the international aspect of this work, the “Directeur Général d’Arts et Métiers ParisTech” authorised the writing of the thesis report in two languages; English and French (decision DG2009-46 of 1er October 2009). Hence, this document is divided in two parts: an extended summary in French (without figures) and the detailed description of the research in English (with illustrations).

Remerciements / Acknowledgements

First and foremost, I would like to thank my thesis director, Prof. Patrick Martin for his invaluable advices based on his expert knowledge. His clear, concise and pertinent remarks during various meetings helped setting the research direction.

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I am forever indebted to my mother and my late father for their belief and confidence in me. My heartfelt thanks to Zafar uncle, Aunty and Shahzeb for always believing in me and without whose help, all this would not have been possible. I thank my brothers Dr. Shahab and Dr. Farhan and sister Dr. Shehla for being a constant source of inspiration and motivation.

I owe my deepest gratitude to my wife Mahwish, for being a pillar of support during all the hardships and difficulties that we encountered during this journey. I thank her for bearing with me in times of stress and despair. Without her constant support and encouragement this would not been possible. Finally, I thank my son and best buddy Abdullah! I love you my son!

Lastly, I gratefully acknowledge my funding agency “Higher Education Commission of Pakistan”, who made my PhD possible.

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Abbreviations

ABC: Activity Based Costing

FMS: Flexible Manufacturing Systems

DML: Dedicated Manufacturing Lines

RMS: Reconfigurable Manufacturing Systems

RMT: Reconfigurable Machine Tools

AD: Axiomatic Design

FBS: Function-Behavior-Structure

MASON: MAnufacturing's Semantics Ontology

CN: Customer Needs

FR: Functional Requirements

DP: design Parameters

PV: Process variables

F: Function

B: Behavior

S: Structure

PI: Performance Indicators

Résumé étendu en Français

Introduction

Ces derniers temps, il a y eu beaucoup de développement et d'expansion de plusieurs nouveaux paradigmes de la fabrication. La réduction des séries, l'évolution rapide des produits ont conduit à l'apparition du concept de « Reconfigurable Manufacturing Systems (RMS) » afin de répondre aux objectifs contradictoires de productivité et de flexibilité. Ils se situent entre les Systèmes Manufacturiers Flexibles (FMS) et les Lignes Transfert Dédiées (LTD) ou les systèmes de production dédiée (DML).

Cette nouvelle avancée a nécessité le besoin de méthodologie de conception visant à répondre à la question : « Comment optimiser la conception du processus d'usinage et du système de production reconfigurable en tenant compte des interactions entre le processus et les ressources, et des contraintes technologiques imposées par les pièces à fabriquer ? »

Les travaux les plus avancés ont été réalisés au « Engineering research centre for reconfigurable manufacturing systems » à l'Université du Michigan. Ainsi, il a été défini les tendances futures vers la standardisation des composants et des modules dans tous les aspects de reconfiguration. Parmi ces aspects sont cités : la reconfiguration des systèmes de fabrication, des machines-outils, des processus, des machines de contrôle, des systèmes de communication. Le premier concerne la conception du système (architecture, interface entre machines supervision, etc.), le deuxième concerne la conception des machines-outils (partie opérative, interface entre modules) …

Ces travaux de thèse visent à répondre à la question ci-dessus en se focalisant sur la co-conception des processus d'usinage et des configurations cinématiques du RMS.

Ainsi, ce mémoire s'articule autour de quatre chapitres

Le chapitre 1, permet de situer le concept général de RMS et les travaux existant vis-à-vis de la conception du système de production reconfigurable. Il propose une étude bibliographique des systèmes manufacturiers actuels en se focalisant plus particulièrement sur les systèmes manufacturiers dédiés, les systèmes manufacturiers flexible et systèmes manufacturiers reconfigurables. Egalement, il propose une synthèse sur les différents travaux existant dans le domaine de conception de machines outils reconfigurables. Cette représentation permet de délimiter le cadre de ce travail en précisant les données d'entrées.

Dans le chapitre 2, une démarche de conception d'un système de fabrication reconfigurable est proposée. L'approche Axiomatic Design (AD) a été déployée pour la conception des systèmes de fabrication dans le cadre du Lean Manufacturing (Manufacturing system design decomposition (MSDD)). Nous avons identifié qu'il y a besoin d'un lien entre le niveau stratégique et le niveau opérationnel. Ainsi, dans le chapitre 2, nous avons proposé un domaine supplémentaire : Indicateur de performance qui permet de faire le lien entre les activités de conception (explicitées dans le Lean Manufacturing) et les solutions physiques (explicitées dans ces travaux). Nous proposons de coupler à AD à l'approche FBS pour l'évaluation de ces indicateurs de performance.

Le chapitre 3 est destiné à répondre à la problématique de génération de gamme et de structure d'un RMS. Nous avons développé une approche algorithmique : L'algorithme permet de faire la liaison entre les fonctions que l'on souhaite obtenir et la structure qui va nous le permettre, et ainsi explorer l'ensemble des solutions possibles. Ce passage est fait par génération du comportement caractérisé par les opérations (opérations d'usinage, de changement d'outil, de changement de poste, …). Le développement de l'application est fait en VBA et Excel comme interface. Cet algorithme est actuellement validé sur 3 pièces tests du domaine de l'automobile.

Le chapitre 4 se focalise sur la nécessité d'évaluer les solutions générées - les critères d'évaluation sélectionnés sont le coût, le temps, l'étendu de famille de produit et la qualité. Parmi l'ensemble des critères celui relatif à la qualité (déjà défini comme un indicateur de performance au chapitre 2) est détaillé. La qualité est définie en termes de satisfaction des tolérances géométriques. Les solutions structurales sont modélisées sous forme de graphes. Nous proposons des heuristiques permettant le transfert des graphes issus du chapitre 3 en graphes supports de l'analyse de la qualité. « Internal Tolerance Condition (ITC) » de chaque solution sous forme d'un graphe est calculé.

La conclusion globale présente une synthèse de ces travaux et permet de proposer des pistes pour des travaux de recherche ultérieurs. L'augmentation du niveau de reconfigurabilité du domaine structural au domaine processus est discutée. Le besoin de faire une évaluation multicritère avec les autres critères d'évaluation comme le temps, le coût … est soulignée. Aussi une agrégation des indicateurs de performance doit être mise en œuvre.

1. Chapitre 1 : Système de Production Reconfigurable

Pour la production d'un produit spécifique, les chaînes de montage dédiées sont utilisées, ou les lignes de transfert ont été conçues. Elles étaient économiquement viables tant que les temps et les volumes de production étaient très importants, et la demande était sur une longue période de temps. L'évolution rapide de la conception et l'augmentation de la fréquence d'introduction de nouveaux produits dans le marché avec la nécessité de fabriquer les produits de haut qualité à des prix raisonnables a augmenté le besoin de système de fabrication rapide et adaptable. Ces conditions contradictoires sont satisfaites en concevant un système de fabrication qui est basé sur une famille de produit et possède la capacité de répondre aux changements du marché c.à.d. le système de production reconfigurable.

Cette technologie reconfigurable nécessite une partie “matérielle” et “logicielle” modulaire. C'est-à-dire des machines outil modulaires (cinématique modifiable), et une architecture ouverte du système de commande.

Depuis plus de 15 ans, des travaux de recherche en matière de démarche de conception de système de production reconfigurable ont été effectués. Olivier Garro en 1992 sous la direction du Pr. Patrick Martin au sien du Centre de Recherche en Automatique de Nancy – (CRAN) dans sa thèse a travaillé sur les aspects opérationnels des machines modulaires ayant des architectures parallèles. En Allemange, le project « METEOR 2010 – Multi Technology Based Reconfigurable Machine Tool 2010 », travaille sur le développement et la standardisation des composants intervenant dans les machines outil reconfigurables. Notre étude bibliographique conclu qu'il y a un besoin d'une méthodologie de conception particulièrement orientée vers RMS. Cette méthodologie doit traiter les besoins fonctionnels comme entrées et générer les solutions architecturales comme sorties.

1.1. Objectif

Le travail développé dans ce mémoire concerne le domaine des systèmes de production reconfigurables. L'objectif de ce travail est de répondre à la question suivante:

« Comment optimiser la conception du processus d'usinage et du système de production reconfigurable en tenant compte des interactions entre le processus et les ressources, et des contraintes technologiques imposées par les pièces à fabriquer ? »

Les problématiques liées à la conception et à la mise en œuvre d'un RMS sont la conception globale du système reconfigurable, la conception de chaque machine reconfigurable, la conception de la partie commande, la validation et les réglages.

Dans nos travaux, nous nous concentrons sur les aspects technologiques d'un RMS. Ils sont les facteurs qui sont directement liés aux coûts, à la qualité, … de realisation des entités pour une famille de produit. Nous nous focalisons sur le developpement d'une methodologie pour la conception de système de production et la structuration des indicateurs pour évaluer les solutions générés.

1.2. Système de production

La production est définie comme étant un ensemble des transformations successives passant de l'état de matières premières à l'état de produits finis (Dano, 1966).

Chacune de ces transformations correspond à des modifications physiques ou chimiques des matières traitées. Notre travail est particulièrement orienté vers la génération des configurations cinématiques des machines outil d'usinage. Selon ElMaraghy (ElMaraghy, 2005), les systèmes de production peuvent être classifiés en trois groupes basés sur leur productivité et flexibilité :

1.2.1 Systèmes manufacturiers dédiés (DML)

Les Systèmes Manufacturiers Dédiés (SMD) (*Dedicated Manufacturing Lines - DML)*) ou les Lignes Transfert Dédiées (LTD) ont été développés dans le secteur de l'automobile (production de masse) où la rationalisation de la fabrication répond à un objectif de productivité. Chaque ligne dédiée est typiquement destinée à produire une pièce unique à un haut rythme de productivité. Chaque station de la ligne est spécialisée pour faire une opération d'usinage toujours identique et toujours au même endroit sur la pièce (perçage, fraisage, lamage…).

Les DML sont devenus moins pertinent par rapport à l'évolution du marché. Ils sont économiquement viables quand la demande de produit est importante et fixe.

1.2.2 Systèmes manufacturiers flexible (FMS)

Les Systèmes Manufacturiers Flexibles FMS ont été introduit dans les années 1980 (Mehrabi et al, 2002). C'est une technologie qui vise à rendre flexible l'ensemble de l'outil de production permettant de préparer, de s'adapter aux divers changements de son environnement, sans qu'il y ait besoin d'engager de nouveaux investissements en biens d'équipement, ou d'engendrer de longues pertes de temps. Les FMS peuvent être un ensemble des modules ayant plusieurs directeurs de commande, ou un seul système de production flexible (Figure 1).

Les FMSs ont été spécialement développés pour répondre à la fois aux contraintes de productivité et de flexibilité. Malheureusement, ils présentent un certain nombre d'inconvénients :

- très haut cout initial, l'investissement et les charges financières de ces équipements (hardwares, softwares),
- bas taux de production à cause de non simultanéité des opérations,
- leurs capacités de production sont souvent fixes et très inférieures aux objectifs visés.

Selon (Mehrabi et al, 2002), les entreprises industrielles mettant en place des FMS constatent le plus souvent que le niveau de flexibilité n'est pas conforme aux objectifs visés. De plus, la productivité des FMS est largement inférieure aux DML avec des coûts d'investissement initiaux et de fonctionnement plus importants. Pour répondre à ces exigences et difficultés, les RMS sont proposées.

1.2.3 Systèmes manufacturiers reconfigurable (RMS)

La définition générale des RMS a été donnée par Y. Koren (Koren, 1999).

« Le système de fabrication reconfigurable est un système qui est conçu au départ pour le changement rapide de structure, aussi bien des composants et que des logiciels. Il peut être ajusté rapidement à la capacité et à la fonctionnalité de production, pour une famille de pièce, en réponse aux changements rapides du marché ou des conditions de normalisation ».

Une comparaison entre les trois systèmes basée sur capacité, fonctionnalité, coût… est faite en tableau 1 qui montre que les RMS permettent d’avoir une flexibilité adaptable aux besoins tout le long du cycle de vie de produit.

L’objectif du RMS est de répondre à des exigences variables et d’assurer une fonctionnalité ajustable avec une forte productivité et des temps d’installation minimaux (Abele, 2006(a)).

1.3. Reconfigurabilité et Flexibilité

ElMaraghy (H.ElMaraghy, 2006) a détaillé la conception, les caractéristiques et les avantages potentiels du RMS. Elle compare particulièrement les RMS avec les FMS. Selon elle, les RMS sont conçus au départ pour un changement rapide de structure et d’informatique. D'autre part FMS est un système ou les machines sont capables de réaliser des opérations en simultanée. C.à.d. les RMS sont conçus avec une flexibilité particulière et FMS sont conçus avec une flexibilité générale. Donc les RMS sont positionnés entre les DML et FMS par rapport la flexibilité et la capacité comme montré en Figure 4 (Hu, 2005).

1.4. Technologies du RMS

Les verrous technologiques ou problématiques liées à la conception et à la mise en œuvre d’un RMS sont :

- la conception globale du système reconfigurable,
- la conception de chaque machine reconfigurable,
- la conception de la partie commande,
- la validation et les réglages.

Dans nos travaux, nous nous concentrons sur les aspects technologiques d'un RMS. Ils sont les facteurs qui sont directement liés à la qualité et au coût des entités qui sont exigées pour une famille de produit.

La partie commune pour les systèmes existants c.à.d. système dédié et système flexible est l’usage de matériel et logiciel fixe. L'essentiel du paradigme RMS est une approche de reconfiguration fondée sur la conception du système qui repose sur la conception de l’architecture qui est ouverte et modulaire. Pour répondre aux exigences, les modules et les interfaces doivent être soigneusement définis. Quelques points importants dans le domaine du RMS (Wendahl, 2005) sont enumerés dessous :

- globalité,
- mobilité,
- scalabilité,
- modularité,
- compatibilité.

1.5. Caractéristiques clé du RMS

Le RMS doit être conçu en intégrant le concept de reconfigurabilité. A ce jour, les concepts de reconfigurabilité sont établis par un ensemble de 6 principes (Koren et Ulsoy, 2002 ; Spicer et al, 2002) :

- ***la « modularité »*** est la faculté de regroupement des fonctions assurées par des composants du système (logiciel et matériels) de façon qu'ils soient interchangeables (Koren et al, 1999). Le type de modules de base définit la granularité du système,
- ***l'« intégrabilité »*** est la faculté d'intégration rapide des modules constitutifs du système par un ensemble d'interfaces mécaniques, de connectiques pour la gestion et commande des informations,
- ***La « convertibilité »*** est la faculté de transformation de la fonctionnalité du système, des machines et de la commande existants afin de s'adapter aux nouveaux besoins de production,
- ***L'« extensibilité »*** est la faculté d'ajustement à la capacité de production du système en le reconfigurant au coût minimal, en un minimum de temps et pour une large gamme de capacités;
- ***La « personnalisation »*** est la faculté d'adaptation à une flexibilité personnalisée (juste nécessaire au bon moment) du système et des machines pour répondre à de nouvelles spécifications d'une famille de produits;
- ***La « diagnosabilité »*** est la faculté à identifier automatiquement l'état courant du système et de la commande afin de détecter ainsi que de diagnostiquer les sources de défaillances en vue de les corriger rapidement.

Modularité, interchangeabilité, et diagonasabilité réduit le temps de reconfiguration et la personnalisation et convertibilité réduit le coût de la reconfiguration.

1.6. Conception de la machine outil reconfigurable (RMT)

Généralement, les approches de conception des RMS utilisent une bibliothèque de modules d'usinage. La conception de RMT doit être basée sur les deux approches:

- Conception modulaire : C'est un facteur clé de la conception d'une RMT. Il permet à la machine d'être reconfigurée par simple ajout ou enlèvement des modules. La RMT doit être capable de satisfaire les besoins de mouvements spécifiques et d'assurer les tolérances. Landers (Landers, 2006) a proposé une méthodologie pour déterminer les besoins cinématiques automatiquement.
- Conception de système d'information et de contrôle : Comme la bibliothèque des modules, les composants de contrôleurs informatiques sont stockés pour les futures conceptions.

1.7. RMTs existantes

Plusieurs contributions importantes dans le domaine de recherche pour la conception de RMT sont identifiées.

1.7.1 SHIVA

SHIVA est la première tentative de RMT initié par Garro et Martin (Garro, 1992; Garro et Martin, 1993). Ces travaux présentent une méthodologie de conception de la partie opérative de machines-outils en ayant intégré un niveau de reconfigurabilité de manière implicite.

Ces travaux se positionnent au niveau de la conception d'éléments physiques des systèmes de fabrication de produit. Dans ce cadre, ils ont proposé une méthode de conception applicable aux machines outils, basée sur des concepts de modularité afin de parvenir à une réelle intégration de la partie commande.

La synthèse structurale de SHIVA est constituée d'un grand nombre de broches qui réalisent des opérations d'usinage sur une pièce fixe. Les broches travaillent de manière séquentielle ou simultanée. La démarche de spécification permet, à partir d'un cahier des charges décrit en termes d'entités d'usinage, de rechercher des solutions d'architectures fonctionnelles des machines-outils. Garro (Garro, 1992) a proposé un formalisme mathématique basé sur la logique temporelle dans l'objectif de traduire les concepts de simultanéité et/ou d'ordonnancement des opérations d'usinage.

D'autre part, Garro (Garro, 1992) a utilisé le concept de broche-multiple pouvant réaliser plusieurs opérations en même temps mais la prise en compte de la problématique de mise et maintien en position des pièces n'est pas été traité. Les contraintes de génération des processus ont été définies telles qu'elles évitent l'explosion combinatoire.

1.7.2 Arch-Type RMS

En 1996, à l'Université du Michigan, le laboratoire ERC/RmS (Engineering Research Centre of Reconfigurable Machining Systems) conçoit une RMT (Figure 7).

Moon dans son travail (Moon, 2000) propose une méthode de conception de RMT. Il a traité la génération de RMT à broche unique et multiple. Les informations d'entrée nécessaires sont classiquement le type de matériaux, les géométries et les tolérances des pièces constituant la famille de produit ainsi que les conditions de production (cadence, cycles…) et la gamme d'usinage.

La spécificité de son travail réside pour la formalisation des mouvements via une représentation par vecteur dual pour la modélisation géométrique et cinématique de corps rigides en déplacements finis. Il propose une représentation par symboles graphiques des connections (interfaces) en vue de définir les différentes solutions d'architectures.

Enfin, il a développé des outils permettant de définir, concevoir et valider une (RMT). Le projet (Moon et Kota, 2002) se décompose en :

- Définition géométrique des modules ;
- Evaluation de la précision de la machine-outil ;
- Modélisation du comportement dynamique des modules sous ADAMS ;
- Développement de nouveaux modules pour le RMT.

L'applicabilité est discutées en détail en chapitre 3.

1.7.3 METEOR 2010

Le projet allemand « METEOR 2010 » consiste à standardiser les composants des Machines Outils Reconfigurables qui interviennent lors de la constitution d'une machine outil multi technique. Ce travail apporte des réponses sur les principes de modularité, d'intégrabilité, convertibilité et extensibilité pour les machines-outils reconfigurables

Le projet consiste à développer le principe de reconfigurabilité par la modularité et l'adaptabilité des modules de machine outils dédiées à l'usinage. Les modules de cette Machine-outil Reconfigurable doivent respecter : un coût minimum ; une réduction des temps d'indisponibilité (pannes, dégradation, mise en course…); une capacité de réaliser des opérations de tournage, fraisage, de perçage…. La standardisation des interfaces (mécanique, électrique, hydraulique, pneumatique…) est un enjeu majeur de ce type de machine.

1.7.4 Approche de configuration structurale de la machine outil

Shakaba et ElMaraghy ont travaillé sur la génération des configurations de la machine outil reconfigurable (Shakaba, 2007). Ce travail est au niveau opérationnel. Les entrées sont les caractéristiques dimensionnelles /géométriques et les directions des outils des opérations nécessaires à réaliser pour les entités.

Pour la génération des configurations cinématiques, le tableau de précédence entre les opérations d'usinage est considéré comme entrées. Cette approche regroupe les opérations comme « Operation Clusters ». Les sorties sont les configurations de la machine outil, ensemble des modules, les axes des mouvements minimaux et les angles de rotation pour chaque cluster. Une illustration de l'approche est donnée en Figure 8.

1.8. Bilan

Le nouveau paradigme de RMS est un important avancement dans le domaine des systèmes de production. Ces travaux sont définis au sein de la communauté du CIRP (College International pour la Recherche en Productique, International Academy for Production Engineering) et NSF (National science foundation USA).

Les tendances actuelles vont vers l'opérationnalisation des principes de reconfigurablité (modularité, intégrabilité, convertibilité, extensibilité, personnalisation, diagnosticabilité).

La modularité et l'intégrabilité sont généralement obtenues par construction, et les solutions portent essentiellement sur la prédéfinition d'un axe (translation, rotation) où les interfaces de chaque module sont déterminées par des liaisons d'encastrement démontables avec le bâti. Les travaux de Garro (Garro, 1992) est un des premiers à penser à la reconfigurabilité dans le système de fabrication en introduisant la modularité. (Koren et Ulsoy, 2002) pose les principes et engage des travaux dans le cadre des RMS.

En bilan, la conception des Systèmes Manufacturiers Reconfigurable ou des Machines-outils Reconfigurables est un support industriel où s'exprime divers domaines scientifiques (de la mécanique à l'automatique, en passant pas les problématiques d'organisation…). Au travers la littérature, nous avons observé que les méthodologies sont peu développées. Nous avons observé qu'il y a un besoin d'une méthodologie qui traite la partie processus et la partie structurale en même temps.

2. Chapitre 2 : Formalisation et structuration du processus de conception d'un RMS

La conception d'un système de fabrication peut être considérée comme une cartographie des exigences de performance d'un système de fabrication (valeurs des variables décisionnelles), qui décrivent le fonctionnement d'un système de fabrication (Figure 10). Ainsi, la conception d'un système de fabrication est considérée comme une activité cyclique ayant: la définition des objectifs du système ; l'élaboration détaillée des contraintes du système et la mise en œuvre de la conception.

La conception peut être définie comme « *l'interaction entre ce que nous voulons réaliser et comment nous voulons le réaliser* ». Par conséquent, une approche de conception doit commencer par une déclaration explicite de «ce que nous voulons atteindre », puis une description claire de « comment nous allons le réaliser» peut être effectuée. Les méthodes et outils pour la conception de systèmes de fabrication se répartissent en trois grandes catégories: recherche opérationnelle; intelligence artificielle et simulation (Chryssolouris, 1992). Il existe de nombreuses approches de conception qui sont suivie par les concepteurs pour les problèmes d'ingénierie. Il s'agit notamment de Théorie de la résolution des problèmes inventifs (TRIZ) (Altshuller, 1997), Axiomatic Design (AD) (Suh, 2001), fonctions-Comportement-Structure (FBS) (Gero, 1990) ... Ces approches de modélisation et de méthodes d'analyse ont été développées afin de clarifier la conception de systèmes complexes.

Afin d'assurer la mise en relation des objectifs d'évolution issus de la stratégie concurrentielle et les besoins d'évolution du système physique de production, le laboratoire « Production System Design » (PSD) du M.I.T. applique l'axiomatic design (Suh, 1990) pour construire un modèle fonctionnel des relations entre les besoins fonctionnels issus de la stratégie « lean manufacturing » et les moyens pour satisfaire ces besoins (Cochran, 2000). L'axiomatic design distingue le niveau stratégique caractérisé par les besoins fonctionnels et les moyens de les satisfaire et le niveau physique qui représente le modèle du système que l'on étudie. Cependant le modèle développé par le MSDD/PSD est incomplet. En effet, ce modèle ne propose pas d'interface pour permettre le lien entre le niveau stratégique et le niveau physique; il propose des interfaces entre les besoins fonctionnels du processus de conception et les activités de conception du système physique de production.

Notre objectif de conception du système de production reconfigurable (RMS) nous conduit à des questions très importantes pour les quelles nous trouveront les réponses dans le cadre de notre projet. Ils sont:

- Comment formaliser et structurer les processus de conception pour la conception d'un RMS?
- Comment formaliser le lien entre les besoins fonctionnels et les éléments physiques de RMS?
- Comment évaluer une solution de conception et de définir des indicateurs de performance mesurables?

Nous proposons un cadre qui aide les concepteurs de systèmes reconfigurables dans la structuration du processus de conception. Il est basé sur les exigences fonctionnelles de la famille de produit sélectionnée, la structuration des connaissances nécessaires au cours du processus de conception et à définition des critères d'évaluation pour des systèmes de fabrication. L'application de la « Function-Behavior-Structure (FBS) » permettra la définition des caractéristiques fonctionnelles à un niveau d'abstraction adapté, la prise de décision et l'évaluation.

2.1. Approches de conception

La conception d'un système de fabrication possède un ensemble d'objectifs stratégiques qui implique de prendre une série de décisions complexes. La conception d'un système de fabrication inclut: la prise des décisions concernant les équipements, les caractéristiques, les matériels et leur information. Un système de fabrication peut être décrit comme un ordonnancement des opérations des machines-outils et des personnes. Le processus de conception peut être défini comme un processus décisionnel hiérarchique. Seules les approches AD et FBS - sources de nos réflexions sont détaillées.

2.1.1. Axiomatic Design

Axiomatic design est une théorie de la conception proposée par Nam SUH dans les années 90 (Suh, 2001). Cette théorie est basée sur les corrélations entre « ce que nous voulons réaliser-QUOI ? » et « la façon dont nous voulons le réaliser- COMMENT ? ». Les principes d'AD sont la propagation systématique des FRs aux différentes facettes de la conception d'un système. Cette propagation est appropriée à la conception des systèmes de fabrication. Cette théorie repose sur la définition de 4 domaines, 2 axiomes, 26 théorèmes et corollaires et une formalisation matricielle des corrélations. Les 4 domaines (Figure 11) sont :

- Le domaine client qui est composé de 'Customer Attributs (CA)' et qui représente les besoins du client.
- Le domaine fonctionnel qui est composé de 'Functional Requirements (FRs)' et qui représente les Fonctions attendues du produit ou du système.
- Le domaine physique qui est composé de 'Design Parameters (DP)' et qui représente les solutions techniques réalisant les 'FR'.
- Le domaine processus qui est composé de 'Process Variables (PV)' et qui représente les opérations de fabrication des solutions techniques.

Les axiomes sont :

- Le premier axiom s'appelle "Independence axiom" qui indique que l'indépendance des FRs doit être gardée.
- Le deuxième s'appelle 'Information axiom' qui définit l'objectif : minimiser les informations de la conception.

Parmi tous, il a deux domaines principaux, le domaine fonctionnel et le domaine physique. La matrice de conception permet de représenter les corrélations entre les paramètres de deux domaines consécutifs.

$$\{FR\} = [A]\,\{DP\}$$

$$A_{ij} = \partial FRi / \partial DPj \text{ : Sensibilité de la FRi par rapport au DPj}$$

Cette matrice permet de caractériser le type de conception. Dépendant du type de matrice, la conception peut être classifiée comme découplées, quasi découplées ou couplée.

De plus, les paramètres sont structurés d'une manière hiérarchique et arborescente (décomposition) à l'intérieur de chaque domaine. N. SUH propose un processus de conception en Zigzag. Nous pouvons remarquer qu'Axiomatic Design est une théorie ou un objectif cible mais les solutions ne sont que très rarement totalement découplées.

Dans nos travaux, nous avons déployé les principes d'AD pour effectuer la définition des FRs et des DPs pour la conception d'un système de la fabrication reconfigurable. Les relations entre les deux domaines sont explicitées par la construction des matrices de conception à chaque niveau de décomposition. Une analyse de chaque domaine de conception est faite en définissant et en décomposant les facteurs principaux affectant son exécution. La conception conceptuelle montrant les chemins-dépendances de chaque besoin fonctionnel (FR) sur les différents paramètres de conception (DP) est donnée.

2.1.2. Function-Behavior-Structure (FBS) approche

L'approche FBS (Gero 2002) est destinée à améliorer la conception de produits ou de systèmes. Michel Labrousse (Labrousse, 2004) a proposé des définitions génériques de chaque classe. Aussi Hu (Hu et al, 2000) a défini le modèle FBS comme une approche de conception qui représente de manière explicite les fonctions du produit ou du système (le problème), la structure du produit (la solution) et les comportements internes du produit. Les objets sont considérés suivant trois vues (fonctionnelle, comportementale et structurelle) et sont supposés pouvoir être définis en passant successivement d'une vue à une autre. Le but principal de l'approche FBS est de pouvoir représenter la conception d'un système pour un ensemble de processus de transitions distinctes. Dans l'approche FBS (Figure 12), le processus de conception est divisé en huit étapes différentes par lesquelles le concepteur transforme les fonctions F en une description du système D. Ces étapes sont :

- la formulation des fonctions (F) en des comportements attendus (Be),
- la synthèse des comportements attendus (Be) en configurations structurales (S),
- l'analyse de la structure (S) en observant ces comportements réalisables (Bs),
- l'évaluation en comparant les comportements attendus (Be) et les comportements réalisables (Bs),
- la documentation (D) des caractéristiques de la structure,
- reformulation pour la structure (S),
- reformulation pour le comportement attendu (Be),
- reformulation pour les fonctions (F).

2.1.3. Conception axiomatique du système de la production

Pour la conception de systèmes de fabrication, la décomposition dans le domaine fonctionnel et physique est la plus déployée (Suh, 2001; Cochran et Reynal, 1996).

Pour atteindre les objectifs d'une entreprise, des systèmes de fabrication doivent être conçus pour satisfaire à un ensemble précis d'exigences fonctionnelles basées sur des exigences du client et les contraintes de fabrication (Garro et Martin, 1993). Les travaux récents incluent :

Méthodologie de l'optimal sélection des modules (Chen, 2005)

Les principes d'axiomatic design sont introduits dans une méthode basée sur les entités d'usinage pour la sélection d'un ensemble optimal de modules nécessaires pour la construction d'une machine-outil reconfigurable, qui est capable de produire une famille de produit. Par optimal, il est signifié que la taille de l'ensemble sélectionné est minimale, et, suffisante à la formation d'une machine-outil reconfigurable. Ici, le concept d'entité d'usinage est référé comme des FRs, tandis que les modules structuraux constitutifs de la machine-outil sont référés comme les DPs.

Dans la méthode de Chen, le succès de la conception de RMT dépend de la disponibilité d'un ensemble de modules d'usinage.

Manufacturing system design decomposition (MSDD) et product development system (PDS)

L'approche Axiomatic Design (AD) a été déployée pour la conception des systèmes de fabrication dans le cadre du Lean Manufacturing : « Manufacturing System Design Decomposition » (MSDD) (Cochran 1996 ; Cochran 2000). Pour réaliser tous les objectifs mentionnés ci-dessus, l'approche MSDD est employée. L'objectif de MSDD est d'améliorer le retour sur investissement (ROI). Les principes d'Axiomatic design sont employés dans MSDD. L'objectif est de décomposer la paire de FR-DP de niveau haut en les décomposant aux niveaux bas. On peut remarquer la conservation de la structure hiérarchique d'A.D et l'ajout d'une hiérarchie horizontale (dégrée d'importance). MSDD propose des sous domaines dans l'ordre d'importance sont qualité, résolution des problèmes, rendement prédicable, réduction de temps et réduction de coût opérationnel (Figure 13).

Afin d'assurer la mise en relation des objectifs d'évolution issus de la stratégie concurrentielle et les besoins d'évolution du système physique de production, le laboratoire « Production System Design » (PSD) du M.I.T. applique l'axiomatic design pour construire un modèle fonctionnel des relations entre les besoins fonctionnels issus de la stratégie « lean manufacturing » et les moyens pour satisfaire ces besoins. MSDD distingue le niveau stratégique caractérisé par les besoins fonctionnels et les moyens de les satisfaire et le niveau physique qui représente le modèle du système que l'on étudie.

PDS est une extension du MSDD visant à donner une dynamique à l'aspect statique des paires FR-DP. Cette approche prend la conception du système de fabrication à un niveau dynamique. Dans le domaine des ressources, les dépendances sont employées pour développer une méthodologie d'attribution d'investissement et de ressource.

Le PDS s'applique à la conception de système dans sa totalité. C'est une conception quasi découplé. La Figure 14 montre et illustre clairement l'importance des dépendances dans la conception de système de fabrication. Dans l'environnement de ressource minimal, les dépendances sont employées pour développer une méthodologie de l'allocation d'investissement et de ressource. Le PDS analyse comment l'investissement dans un DP aidera à réaliser une FR.

2.2. Cadre de conception pour un RMS utilisant l'approche AD et FBS avec le domaine de performance intégrée

Cependant le modèle développé par le MSDD/PSD est incomplet. En effet, ce modèle ne propose pas d'interface pour permettre le lien entre le niveau stratégique et le niveau physique ; il propose des interfaces entre les besoins fonctionnels du processus de conception et les activités de conception du système physique de production. L'approche MSDD vise à analyser comment l'investissement dans un DP aide à réaliser une FR (Cochran 2003). Il est important de remarquer que dans cette approche, les DPs sont les activités qui effectuent la définition de la solution physique. Par conséquent, un DP est une activité orientée pour réaliser l'objectif de la conception, mais pas la conception elle-même.

Nous avons observé quelques manques en appliquant l'approche axiomatique pour la conception d'un RMS : le lien entre le niveau stratégique (très développé dans le Lean Manufacturing) et les solutions physiques, et la notion de mesure de performance.

- Premièrement, nous nous intéressons à la construction des relations entre les besoins fonctionnels du RMS et les éléments physiques du RMS. Les (FRs) sont décomposées et classifiées en termes de « étendu de la famille de produit », « capabilités » (qualité, caractéristiques géométriques, précision…), « temps » et « coût ». Donc la FR est une fonction du RMS et un DP est défini comme un élément du RMS.

- Deuxièmement, la notion de mesure de performance n'est pas incluse, c'est-à-dire, on ne sait pas si le DP défini a complètement satisfait la FR sélectionnée ou non. Pour surmonter ce manque, on propose un nouveau domaine d'indicateur de performance (PI) intégré dans l'approche de conception. Ils sont associés aux FRs du RMS et aux DPs du processus de conception. Ils sont évalués à partir des DPs du RMS. La définition d'indicateurs de performances est rendue nécessaire afin d'évaluer les solutions entre elles, ou par rapport à des performances attendues pour effectuer des choix, mais aussi par la nécessité d'évaluer la pertinence d'une activité de conception.

2.2.1. Processus de Conception

Notre approche est basée sur les principes d'AD comme le PDS. Les indicateurs comme la famille de produit, la qualité, le délai de production et le coût sont les critères essentiels pour le système de fabrication. Par exemple, dans le cadre d'axiomatic design pour la conception d'un RMT, une des FRs est « *Le système de fabrication doit être capable de fabriquer tous les produits de la famille de produit* », le DP correspondant est *« L'architecture du système de fabrication »*.

Dans le cadre du déploiement d'Axiomatic Design pour la conception du système physique du RMS, le passage des FRs aux DPs est fait directement et il n'y pas la définition des processus de fabrication nécessaires pendant la transition des FRs aux solutions de RMS. Le passage des fonctions du RMT à son architecture nécessite la définition des processus de fabrication. Pour remédier à ce manque, nous nous sommes intéressés à l'approche FBS.

2.2.2. Intégration de l'approche FBS pour la conception du RMS

Les trois composants principaux de l'approche sont définis (Gero, 1998) comme :

> Fonction : Elles sont les buts de la conception. « Les fonctions décrivent de manière abstraite les finalités d'un objet (processus, produit ou ressource). Les fonctions de service sont formulées indépendamment de toute solution particulière (en particulier de tout choix de structure), alors que les fonctions techniques sont tributaires d'un choix de solution ». (Labrousse, 2004)
>
> Comportements : Ils sont les attributs dérivables de la structure ou prévus de la structure. « Le comportement décrit la dynamique d'un objet. Il peut comprendre un ensemble de lois et de règles (modèles continus) ainsi qu'une suite séquentielle d'états (modèles discrets) représentant l'évolution d'une structure suite à une excitation (ou stimulation) au cours d'un processus donné. » (Labrousse, 2004)
>
> Structure : « Elle permet de spécifier les éléments qui composent l'objet modélisé ainsi que les attributs de ces éléments » (Labrousse, 2004)

Nous avons utilisé les notions de cette approche pour la conception d'un RMS/RMT. Nous avons proposé la formalisation du processus de conception du RMS via FBS (Figure 17) (Baqai et al, 2008). Une procédure d'application de l'approche FBS a été étudiée pour la conception d'une machine-outil reconfigurable à partir de la définition d'un groupe de pièces. La notion d'indicateur de performance (PIs) a été intégrée dans l'approche. Il utilise le concept de mesure de la différence dans la performance désirée /attendue et la performance réelle du système développé comme proposé par l'approche (Gero, 1990).

L'utilisation de l'approche de FBS nécessite l'étude de comment représenter et modéliser les 3 composants principaux dans le cas de la conception d'un RMS ou d'une RMT:

- Pour la conception d'une machine-outil reconfigurable ou d'un système de fabrication reconfigurable, les fonctions sont les buts ou les possibilités prévues. Une partie de ces fonctions est basée sur le groupe de pièces à réaliser.
- Le comportement (Behaviour) décrit la dynamique d'un objet. Dans notre cas, il s'agit principalement des processus que la machine ou le système doit être capable de faire. Ceci dépend des opérations d'usinage exigées pour réaliser complètement le groupe de pièces pour lequel la RMT ou le RMS est conçu. Ainsi le comportement est représenté en définissant / énumérant toutes opérations exigées, leurs conditions d'antériorité, degrés de liberté exigés et les directions probables d'usinage.
- Enfin, une structure représente l'ensemble des solutions proposées. Elle peut être représentée par un ensemble de configurations probables de la RMT/RMS.

De plus, il est possible d'intégrer une distinction entre le Comportement attendu et le Comportement réalisé. Cette distinction entre le comportement attendu et le comportement réel (Structural) est proposée par Gero (Gero 1990). Le comportement attendu découle des fonctions. Il est essentiellement la traduction et la spécification des fonctions. Le comportement réel découle de la structure et il est donc entièrement dépendant des choix de solution. Le but d'un processus de conception est de les faire coïncider autant que possible et de les ajuster si nécessaire. Dans le modèle original de FBS proposé par GERO, le comportement attendu et le comportement réalisable (structural) sont comparés. Mais dans notre cas proposé de la conception d'un RMS ou d'une RMT, la comparaison des processus de fabrication attendus et réalisables peut être très subjective. Par conséquent « comparer et évaluer » sera effectué au niveau fonction. En effet, les fonctions sont relatives aux produits que doit fabriquer le RMS ou la RMT, donc une comparaison peut être faite entre les fonctions attendues et les fonctions réalisables, c'est-à-dire entre les produits fabriqués attendus et les produits fabricables par le RMS ou la RMT. Dans un premier temps, nous nous sommes restreints aux indicateurs mesurant l'efficacité qui résultent de la comparaison entre les fonctions réalisables (qui sont représentatifs des résultats) et les fonctions attendues (qui résultent des objectifs ou des fonctions).

L'application de l'approche FBS peut être divisée en deux étapes (Figure 19): une phase de génération et une phase d'évaluation.

2.2.3. Intégration de domaine de performance

La définition des indicateurs de performance (PIs) est nécessaire afin d'évaluer les solutions par rapport la performance attendus pour faire des choix. Les PIs créent un lien entre MSDD/PDS et l'approche FBS (Figure 20).

2.3. Cadre de conception

Basé sur les principes axiomatiques, un cadre illustrant le domaine de performance en termes des PIs défini pour les FRs données, a été développé (Figure 22). Pour chaque besoin fonctionnel (FR), son Design paramètre (DP : activité de conception) correspondant est défini et après un PI est sélectionné. Les FR, DP et PI au plus haut niveau sont :

FR1= Le système doit être capable a réalisé une famille de produit, pour les contraintes données

DP1= Système de production reconfigurable (RMS)

PI1 = L'agrégation des performances en termes d'étendue de la famille de produit…

La construction des matrices de conception est faite de la manière similaire que MSDD et PDS.:

$$\{FR_{\text{de RMS}}\} = [B]\ \{PI_{\text{de RMS}}\} \quad (2)$$

$$\{PI_{\text{de RMS}}\} = [C]\ \{DP_{\text{de processus de conception / activités}}\} \quad (3)$$

La relation entre la conception du RMS et les activités de conception avec une notion supplémentaire de PI est illustrée en Figure 21. Les PIs permettent de mesurer l'efficacité des activités de conception et la pertinence des solutions. Ils sont définis à partir de fonctions du système (FRs du système de production) et évalués à partir des solutions du système (DPs du système de production).

Ainsi, nous avons proposé le déploiement d'Axiomatic Design pour la conception du système physique du RMS (Baqai et al, 2007), et un domaine supplémentaire : Indicateur de performance qui permet de faire le lien entre les activités de conception et les solutions physiques. Ces indicateurs de performances font le lien entre les travaux sur MSDD/PSD et nos travaux sur le déploiement d'une approche pour la conception d'un système physique de production (Figure 21).

La conception du RMS basée sur l'approche FBS nécessite deux transitions, du domaine fonctionnel au domaine processus et du domaine processus au domaine structural. Nous avons divisé le processus de conception en 5 étapes :

- Activité A1 : Définition de fonctions exigées,
- Activité A2 : Génération de liste des opérations d'usinage et relation d'antériorité,
- Activité A3 : Génération des gammes et des configurations cinématiques,
- Activité A4 : Evaluation des solutions,
- Activité A5 : Sélection.

Le processus de conception dans le cadre proposé, permet de prendre en compte les processus de fabrication comme le comportement du système.

2.4. L'ontologie de fabrication MASON – Support du processus de conception

L'objectif de ce travail est de définir un cadre de conception et la définition d'un formalisme des connaissances appropriées pour aider à la prise de décision. La base de connaissance pour supporter le processus de conception (transition entre les Functions, Behaviors, Structures) peut être structuré par l'ontologie de fabrication MASON. Les ontologies sont utilisées comme une forme de représentation des connaissances.

MASON a été développé à l'ENSAM en LGIPM en Protégé. Durant son projet de fin d'´etudes (Litzler, 2004), Mr Litzler a spécifié les grandes lignes de l'ontologie, en particulier l'arborescence initiale en Entités, Opérations et Ressources. Une correspondance peut être établie avec la décomposition de P. Martin du concept de production en produit/procédé/ressource. La Figure 25 montre les principaux sous-concepts attachés à ces trois concepts principaux, ainsi que les principales relations qui relient entre eux les concepts. Ce schéma n'introduit cependant qu'un petit sous-ensemble de l'ontologie complète qui contient actuellement autour de 270 concepts et 50 relations.

Dans notre travail, MASON est un support à l'activité de conception. Il fournit des relations sémantiques entre les concepts et les contraintes. Toutefois, il ne fournit pas de relations opérationnelles. Nous avons montré la compatibilité de MASON avec notre cadre.

2.5. Conclusion

Dans ce chapitre, nous nous sommes focalisé sur le développement du cadre pour la conception du RMS et en particulière:

- Un domaine de performance est développé et intégré dans l'approche axiomatique,
- Pour formaliser et évaluer des solutions, l'approche FBS a été adaptée et déployée,

Nous avons montrée la compatibilité de l’ontologie de fabrication MASON à ce cadre de conception du RMS. La conception est réalisée en deux étapes ; génération/conception et synthèse des solutions en première phase ; évaluation et sélection des solutions en deuxième phase.
Chapitre 3 se focalise sur la transition du domaine fonctionnel à la solution structurelle. Les transitions sont réalisées par un algorithme. Le chapitre 4 concerne à l’évaluation des solutions par rapport la qualité d’usinage basé sur les tolérances.

3. Chapitre 3 : F-B-S transition : Génération des gammes de fabrication et configuration architectural du système de production

L'objectif de ce chapitre est de présenter une méthodologie générique pour la conception de système reconfigurable qui est basée sur le cadre présenté en chapitre 2. Cette méthodologie inclut l'exploration de l'espace des solutions par la génération des gammes de fabrication avec ses configurations cinématiques. L'approche de conception est globalement basée sur l'approche FBS (Figure 28, Chapitre 3). Pour une famille de produit ou un groupe des pièces, les entrées sont définies sous forme des fonctions. Les sorties sont définies en terme des structures et de comportements du système. Dans ce chapitre, nous proposons une réponse à la question : « Comment maitriser les transitions entre les trois domaines principaux ? ».

La section 3.1 explique en détail les méthodologies de conceptions existantes et leur applicabilité par rapport à la conception d'un RMS. Dans la section 3.2, les activités pour la conception du RMS sont discutées. Les sections 3.3 et 3.4 se focalisent sur l'algorithme de génération des gammes d'usinage et des configurations cinématiques. Une discussion sur les résultats obtenus et la conclusion sont présentées en dernière.

3.1. Méthodes de Conception

Les RMS ou RMT sont conçus afin de réaliser certaines entités d'usinage. RMT est construit avec des modules d'usinage pour réaliser les variantes d'une famille de produit particulière (Katz, 2007). Les RMS sont composés de RMTs qui ont une configuration spécifique pour un ensemble d'opérations d'usinage.

3.1.1. Détermination des Configurations Cinématiques

La méthode de conception de machines-outils reconfigurables (RMT) proposée par (Moon et Kota, 2002 (a); Moon et Kota, 2002 (b)) a comme entrées: un ensemble des exigences fonctionnelles et un ensemble des gammes ; elle génère un ensemble de configurations cinématiques d'une RMT. Une RMT aura une famille de caractéristiques d'usinage. Comme montrée dans Figure 29, la synthèse d'une RMT commence par l'expression des besoins d'usinage et des informations sur la configuration actuelle. Dans le cas d'une nouvelle machine, il n'y aura pas d'information sur la configuration actuelle. Les exigences et règles d'usinage permettent le contrôle de la conception de cette RMT. Selon Moon, au cours du processus de conception, un concepteur ou l'équipe de conception va faire les étapes suivantes:

- Interpréter les exigences et identifier les données nécessaires de la gamme.
- Sélectionner la référence de la machine à l'aide de base de données.
- Construire la fonction-structure graphe en utilisant les besoins de mouvements et de la référence choisie.
- Compléter le graphe des connexions par la recherche des modules disponibles.
- Finaliser la solution graphique par intégrant la fonction-structure graphe dans le graphe des connexions.

Une synthèse de l'approche est proposée en Figure 29.

"Li Chen et al" (Chen, 2005) ont présenté une méthode fondée sur l'ensemble des modules optimale (minimum et suffisant) nécessaires à la constitution d'une machine-outil reconfigurables pour la production d'une famille de produit. Cette méthode de conception d'un RMT repose sur une série de modules disponibles.

Récemment, Shakaba et ElMaraghy (Shakaba, 2007), ont proposé une méthode pour la génération des configurations cinématiques basée sur les entités d'usinage. L'approche intègre la sélection des machines et la détermination de leurs configurations.

De la discussion ci-dessus, nous pouvons conclure que les approches classiques de génération des configurations d'une RMT intègre les exigences fonctionnelles et un ensemble de gammes comme entrées. De plus, elles exigent une bibliothèque de modules contenant un ensemble de modules qui peuvent être associés aux différentes opérations d'usinage. Ainsi la génération d'un ensemble de configurations cinématiques viables est réalisée (Lenders et al, 2001). Le processus conventionnel de génération de configurations structurelles est montré en Figure 30.

En synthèse, la majorité des approches de conception des configurations cinématiques d'un RMS ou d'une RMT de la littérature se focalisent sur le passage : processus d'usinage à configuration cinématique nécessaire. Nous notons que l'une des entrées de ces approches est le processus d'usinage.

3.1.2. Génération des gammes

Les gammes d'usinage sont le lien entre les entités géométriques des pièces et les configurations cinématiques de la RMS (ElMaraghy, 2009). La conception du processus de fabrication de pièces usinées est un élément clé du dialogue entre les concepteurs et les fabricants d'un produit. Dans cette optique, un outil d'aide à la conception automatique des gammes devient un lien indispensable entre la Conception Assistée par Ordinateur et la Fabrication Assistée par Ordinateur. Un des points essentiels du développement d'une telle passerelle repose sur la capitalisation et la structuration des connaissances métiers du préparateur en lien avec les définitions fonctionnelles du produit et les capabilités des moyens de production (Halevi, 1992).

Automatiser les gammes de fabrication revient à comprendre et à généraliser les mécanismes permettant l'élaboration des gammes pour en tirer un certain nombre de concepts et principes. Un système d'aide à la conception de gammes doit permettre à l'expert de générer rapidement un ensemble de gammes technologiquement viables, parmi lesquelles il peut choisir et approfondir des problèmes spécifiques.

Le processus de détermination des séquences d'opérations d'usinage à partir des spécifications de la pièce est appelé la génération du processus d'usinage (Tollenaere, 1998 ; El Wakil, 1989 and Wang, 1991).

Les approches de génération de processus reposent sur les deux principaux raisonnements qu'emprunte un expert gemmiste lors de la création d'une gamme d'usinage : le raisonnement par analogie et le raisonnement purement génératif. La Figure 31, basée en partie sur les travaux de (GAMA, 1990 ; Villeneuve, 1992) propose une synthèse de ces approches et outils.

Variante : L'approche par variante repose sur ce premier type de raisonnement de l'expert. L'ensemble des pièces déjà réalisées dans l'entreprise sont classées selon leur morphologie, leur gamme d'usinage (gamme type ou enveloppe) et d'autres caractéristiques intrinsèques jugées pertinentes et discriminantes. Lors de la réalisation d'une nouvelle pièce, il est alors possible de retrouver l'ensemble des cas semblables et donc de sélectionner les gammes correspondantes (Anselmetti, 1994 ; Chang, 1985). Cependant l'emploi d'une telle méthode nécessite une capitalisation très importante de l'ensemble des savoir faire de l'entreprise qui s'accompagne de son lot de difficultés : pérennité des gammes et solutions techniques utilisées, manque de flexibilité (en effet, il est impossible d'ajuster une gamme si la pièce à traiter diffère localement des références codées) (Bernard, 2002). Cette approche, bien que nécessitant une durée de capitalisation de connaissances importantes, est efficace dans le traitement des gammes types.

Générative : A cette approche par variante s'oppose l'approche générative. Cette dernière consiste non pas à modifier ou retrouver une gamme déjà créée mais plutôt à en concevoir une nouvelle dès qu'une pièce est à réaliser. Ce ne sont plus le problème et sa solution qui sont capitalisés (la pièce à réaliser et sa gamme) mais la démarche permettant de passer de l'un à l'autre.

Certaines solutions de génération de processus peuvent être citées comme exemple :

- La génération reposant sur des outils de l'intelligence artificielle, comme par exemple PROPEL (Brissaud, 1992) ou PART (Van Houten, 1989).
- La génération par processus type qui associe à une entité d'usinage donnée plusieurs processus entièrement décrits. Puis l'ensemble des processus sélectionnés est ordonné (Park, 2003 ; Elmaraghy, 1993).
- Les approches basées sur le concept de la Génération Ascendante de Processus (GAP), qui proposent de générer la gamme d'usinage en générant les différents états de la pièce allant de son état final à son état brut, au fil des opérations d'usinage (Villeneuve, 1990).

Système expert

Le premier système expert GARI, a été développé dans les années 1980s. Il était dédié pour la génération de la gamme (Descotte, 1981). Pour comprendre le fonctionnement d'un tel outil, il est nécessaire d'en détailler les composants et leurs rôles. Les systèmes experts sont constitués de deux principaux éléments.

- **Une base de connaissances** : Elle est constituée de deux sous ensembles :
    - La base de faits : Cette base de faits est la mémoire de travail du système expert. Elle contient l'ensemble des variables utilisées, les réponses de l'utilisateur aux questions posées par l'outil et les faits déduits par le moteur d'inférence.
    - La base de règles : C'est elle qui capitalise le savoir faire et les connaissances de l'expert. Ces règles sont formalisées de la sorte : Si <condition(s)> Alors <conclusion(s)> où la conclusion devient un nouveau fait qui est ajouté à la base de faits.
- **Moteur d'inférence** : Le moteur d'inférence est avant tout un dispositif permettant d'inférer de nouvelles connaissances à partir de sa propre base de faits. C'est cette partie qui réalise concrètement le raisonnement.

Propagation par contraintes (PPC)

L'approche par programmation par contraintes est la seconde approche analysée pour la génération de processus. Elle est intéressante car elle est proche du travail des concepteurs, qui doivent trouver une solution respectant un nombre important de contraintes, exigences et normes. Nous nous sommes logiquement intéressés à cette approche pour la génération de processus ou plutôt pour la sélection de processus viables considérant un ensemble de contraintes.

La Programmation Par Contrainte (ou PPC), bien qu'apparue dans les années 70 (Waltz, 1972), n'a réellement émergée qu'à partir des années 90. A la différence du calcul formel qui propose de transformer les contraintes (usuellement sous la forme d'inéquations et équations) afin d'obtenir formellement les valeurs des variables, la PPC agit non pas sur les contraintes mais opère une réduction du domaine de définition des variables.

Un problème de satisfaction de contraintes fait correspondre à un ensemble de variables appartenant à un domaine de définition, un ensemble de contraintes qui relient les variables entre elles. Une méthode de programmation par contraintes se définit par :

- Le domaine des variables. Celles-ci sont typées, elles peuvent être : réelles, symboliques, booléennes, rationnelles ou ensemblistes.
- Le type de contraintes, qui peut être comme par exemple numérique (équation + inéquations), booléen, ensembliste ou de typage. Les contraintes peuvent également être symboliques, algorithmiques ou formalisées sous la forme de tableaux ou d'abaques.

Dans le cadre de ce travail nous avons appliqué l'approche PPC pour générer les gammes d'usinage. La PPC permet de rechercher toutes les solutions c'est-à-dire de les « énumérer ». Dans la méthode, une contrainte est en toute généralité une « relation » entre des variables mathématiques. Cette relation peut être de type numérique, de typage, booléen ou symbolique. Une méthode de PPC se définit des variables ou constants (entières, réelles, …) et des contraintes (conditions, valeurs de fonction…). La méthode procède en deux étapes c'est-à-dire réduction des intervalles de définition de chaque variable et de propagation des contraintes sur les intervalles de définition de chaque variable. Le logiciel Contrainte Explorer (CE) (Zimmer et al, 2004) a été utilisé. Le logiciel CE explore et analyse les étendues des variables définies et puis propage les contraintes données et donne un domaine de solution réduit. Pour l'application de la PPC, les entités doivent être réalisées par des opérations d'usinage ; les contraintes relatives à la compatibilité entre entité et opération portent sur les directions, les dimensions, les interactions topologiques, ... La liste des opérations, des antériorités, des accessibilités, des mouvements…. fait des domaines à réduire. Une copie d'écran des solutions est montrée en Figure 32.

Suite à la mise en œuvre de la transition F-B (entités – opérations), nous avons conclu que l'outil de propagation des contraintes peut difficilement automatiser la transition B – S (opérations – configurations cinématiques). Les types et nombre de variables décrivant les structures (configurations cinématiques) ne sont pas fixes et changent en fonction des valeurs des variables décrivant B (les opérations d'usinage).

Reconfigurable process plans (RPP)

L'approche RPP a été proposé par H.A. ElMaraghy (ElMaraghy, 2006(a) ; Azab et ElMaraghy, 2007(a)). Cette approche concerne les variantes de processus d'usinage dues aux changements des besoins fonctionnels.

Deux critères ont été utilisés dans le RPP. Tout d'abord, le temps de reconfiguration, qui n'ajoute aucune valeur, est réduit au minimum afin d'atteindre à une gamme qui minimise le niveau de reconfiguration. Deuxièmement, un indice de gamme, qui mesure le niveau et le coût des modifications, a été ajouté. RPP traite les variantes de gamme à la suite de l'évolution des pièces et des produits. RPP aide le gammiste pendant le processus décisionnel par rapport l'association des machines et l'ordonnancement des opérations.

3.1.3. Bilan

Au regard des travaux existant, nous pouvons conclure que pour la génération des configurations cinématiques, il est nécessaire d'avoir les gammes d'usinage et les spécifications fonctionnelles comme entrées. D'autre part, la génération des gammes nécessite les spécifications fonctionnelles et les configurations cinématique comme entrées (Figure 33). Dans le cas de la conception du RMS, les gammes d'usinage et les configurations changent en fonction des besoins fonctionnels.

De plus, les approches classiques de génération de gamme basées sur l'identification des accessibilités et la recherche d'un minimum de posage connaissant les structures des machines sont obsolètes avec les RMS. De ce fait, l'approche de génération de gamme doit prendre en compte les aspects multi broche et multi structure cinématique en parallèle des RMS, et l'objectif de minimisation des temps et coûts de fabrication. Pour répondre à cette problématique de génération de gamme et de structure d'un RMS, nous avons développé une approche algorithmique qui va être expliqué dans les sous sections suivantes.

3.2. Méthodologie de conception et activités de conception

La méthode de conception est basé sur l'approche FBS, qui présente deux transitions, premièrement du domine fonctionnel au domaine comportemental (processus), deuxièmement du comportemental au domaine structure. Le processus de conception est divisé en cinq activités comme illustré en Figure 24. Cette approche algorithmique a été appliquée sur 3 pièces automobiles (CAI (la pièce CAI illustrera : couvercle arbre intermédiaire) et implémenté en VBA.

3.3. Génération des séquences d'usinage et des relations d'antériorités (A2)

L'objectif de cette activité est de générer la liste des opérations nécessaires et les relations d'antériorité. Les entrées sont l'ensemble des spécifications fonctionnelles c'est-à-dire la description des pièces que doit réaliser le RMS, cette description inclut la description du groupe des entités d'usinage, les interactions topologiques, … Figure 36 montre les entrées, la sortie, les ressources et les contrôles de cette activité. Dans la suite, chaque concept est détaillé :

- Entrées : Entités d'usinage et interactions topologiques
- Contrôles : Cartes de visite

- Sorties : Séquence d’usinage et matrice d’antériorité

3.3.1. Entité d’usinage

Le terme "Entité" correspond au terme anglais "Feature". Ce concept apparaît initialement dans les années 80 comme l’objet de rapprochement entre les modèles de description des pièces (métier de concepteur) et les modèles de préparation à la fabrication (métier de gammiste). Pour l’automatisation des gammes d’usinage, le concept d’entité est pertinent dans la mesure où il supporte la complexité du problème qui est intimement lié au modèle produit, aux bases de données technologiques et à la formalisation de l’expertise en fabrication.

Cependant, puisque ce concept d’entité est employé par les intervenants de différents métiers, à différentes étapes du cycle de vie du produit, une même entité géométrique est perçue de façon différente par chacun de ces intervenants. Ainsi, comme l’illustre la Figure 37, à un simple trou alésé sont associées trois vues : la vue géométrique qui identifie un cylindre, la vue fabrication qui reconnaît un perçage et la vue conception qui associe a cette entité une fonction de passage de vis.

Appliqué au domaine de la génération de processus d’usinage, le groupe GAMA (GAMA, 1990) propose la définition d’une entité d’usinage comme étant : « *Une forme géométrique et un ensemble de spécifications pour lesquels un processus d’usinage est connu. Ce processus est quasi indépendant des processus des autres entités.* »

Dans le contexte de pièce CAI, nous avons 3 trous axiaux, un plan et deux trous taraudés. Chaque entité est décrite avec ses informations géométriques (Figure 43) et ses informations techniques (Figure 44).

3.3.2. Interactions topologiques

Les interactions topologiques sont les caractéristiques de situation d’une entité d’usinage définies par rapport à son environnement pièce. Durant le processus de raisonnement de génération des gammes d'usinage, l'expert gammiste applique différentes règles qui intègre ces contraintes liées au contexte de chaque entité. Dans le cas des interactions topologiques, l’analyse de la pièce n’est que géométrique, la Figure 45 Topological Interactions - example (Villeneuve, 1990) propose un exemple de modèle des interactions entre entités axiales (Villeneuve, 1990).

Les relations topologiques permettent de caractériser les relations entre deux entités voisines. Nous avons définie les interactions possibles entre les entités d’usinage : débouche dans, débouche coaxial,… (Figure 46). Cette taxinomie est basée sur celle proposée par Villeneuve.

Une illustration de la notion d’interaction topologique sur la pièce CAI est donnée en Figure 47. Chaque relation est définie via un code numérique, pour facilité la détection automatique par une application informatique.

3.3.3. Carte de visite

Ce concept de capitalisation et de formalisation des connaissances, dans sa définition originelle (Villeneuve, 1990; Villeneuve, 1993 ; Etienne, 2006) se présente sous la forme d’un tableau (Figure 48) dans lequel l’expert peut expliciter quels sont les domaines de validité d’un processus de fabrication : c’est la solution utilisée qui porte son domaine d’utilisation. Cette approche, facile à mettre en œuvre et assez naturelle à enrichir, reste cependant limitée : l'expert ne peut agir que sur un ensemble de paramètres caractéristiques figés.

Le concept d'OSE (Ben Younes, 1994), permet une sélection des outils pour une entité d'usinage donnée. Ce concept est une évolution des cartes de visite et se décompose en deux étapes :

- Description du contexte d'usinage à l'aide de trois modèles : les entités (les formes à réaliser), les séquences (qui peut être une succession de processus) et les classes d'outils (regroupement fonctionnel d'outils par famille).
- Association de ces trois concepts afin de retranscrire dans un environnement objet les choix d'un expert gammiste. Ces relations et les domaines de validité des paramètres descriptifs des entités sont retranscrits dans une table d'OSE.

Cette approche permet grâce à cette formalisation des connaissances propres à une entreprise, la sélection des outils pour une entité d'usinage donnée.

A partir des formalismes étudiés précédemment, nous proposons une adaptation des cartes de visites (Figure 51) et une formalisation via l'ontologie MASON (Figure 50).

3.3.4. Séquences d'usinage

Les séquences d'usinage sont définies comme une série d'opérations qui peuvent être interruptible (Sabourin et Villeneuve, 1996). Une séquence est un ensemble d'opérations d'usinage ordonnées afin de réaliser une entité.

L'approche algorithmique consiste en la construction de l'arbre des séquences capables de réaliser chaque entité géométrique. A partir de l'ensemble des séquences, les pré-gammes sont générées en explorant l'ensemble des combinaisons possibles (Figure 55).

Dans notre étude de cas, nous définissons une pré-gamme comme un ensemble d'opérations d'usinage contraintes par des conditions d'antériorité qui ont été définies à partir des interactions topologiques entre entités. Le processus de génération de séquences et de ses pré-gammes est illustré en Figure 54.

3.3.5. Matrice d'antériorité

Les contraintes d'antériorité sont définies entre les opérations d'usinage. Les gammes faisables doivent prendre en compte des contraintes de précédence. L'antériorité est définie entre

- soit deux opérations d'une même séquence d'usinage, par l'ordre de ces opérations donnée dans les tableaux des séquences,
- soit deux opérations réalisant deux entités en interaction topologique (Halevi, 1995), par les règles de précédence en fonction de la nature de l'interaction.

3.3.6. Illustration

La pièce CAI est choisie pour illustrer les étapes de l'activité A2. Les paramètres intrinsèques pour les entités axiales et fraisage sont montrés en Figure 43. Les orientations des entités avec ses directions d'accessibilité sont stockées dans un ficher Excel « Part_Groupe » (Figure 44). Les interactions topologiques entre les six entités d'usinage sont données en Figure 57. Un code numérique est donné à chaque relation topologique pour les manipulations.

En utilisant les cartes visites, les pré-gammes pour la pièce CAI sont générées (Figure 55). Dans cette figure, chaque ligne représente une pré-gamme qui est une possibilité à explorer. En utilisant les tableaux des séquences et des interactions topologiques, la matrice d'antériorité est générée (Figure 57). Les valeurs « 0 », « -1 », « 1 », « 2 » dans la matrice représente sans interaction, avant, après et n'est possible en même temps.

L'application est illustrée en Figure 57 pour pièce CAI. Les tableaux de précédence pour les pièces autres deux pièces : CDV et CPHC sont donnés en Annexe B et Annexe C.

3.4. Génération des gammes et des configurations cinématiques (Activité A3)

La première phase de génération/conception/synthèse des solutions inclut deux activités : la transition de l'aspect fonctionnel à l'aspect comportemental et du comportement à la structure. Dans le paragraphe précédent, nous avons détaillé la génération des pré-gammes qui constituent une ébauche de l'aspect comportemental. Pour la génération détaillée des gammes d'usinage et des configurations cinématiques, nous avons expérimenté une approche algorithmique et déterministe pour cette phase. Cette approche s'inspire du mécanisme d'énumération contrôlée de la propagation de contraintes :

Cette étape consiste à explorer l'intégralité de l'ensemble des solutions pour les gammes et les configurations du RMS (Moon, 2002) qui sont potentiellement possibles. Dans le contexte des systèmes de fabrication reconfigurables, la génération des gammes doit prendre en compte la possibilité de réaliser en simultanée différentes entités avec plusieurs broches et chaines cinématiques. Habituellement, pour la génération de la gamme détaillée, le gammiste raisonne plutôt avec le critère : nombre de posages (regroupement des entités ayant des accessibilités compatibles et/ou ayant des contraintes de précision entre elles afin de réduire le nombre de posages), qu'avec les critères : temps et coût en assurant la qualité (Garro, 1993). De ce fait, nous ne pouvons pas appliquer les approches génériques de génération de gammes dédiées aux systèmes de fabrication flexibles (centres d'usinage, …) (Figure 58).

Nous proposons ainsi une démarche itérative dédiée aux systèmes de fabrication reconfigurables ou dédiés (sans prendre en compte les contraintes de mise en position de la pièce), basée sur 6 grandes étapes, (Figure 59) visant à définir un ensemble de gammes alternatives structurées sous forme d'un arbre. Chaque branche de cet arbre représente une ou plusieurs opérations réalisées sur un poste par une structure. Chaque étape de l'algorithme est détaillée par la suite. Ces étapes s'appuient sur une représentation des solutions sous forme de graphe.

3.4.1. Graphe

Il a été nécessaire de développer un formalisme d'enregistrement et de traitement des solutions. Ce formalisme doit permettre de représenter les gammes générées et les configurations cinématiques du RMS. La solution proposée sous forme de graphe est fortement inspirée des graphes proposés par F. Villeneuve. Les nœuds représentent un état du système (pièce+ RMS) et les arcs représentent une opération d'usinage, de changement d'outil, … (action du RMS). Etant donné que ces graphes doivent permettre de représenter une gamme d'usinage d'un RMS, ils doivent permettre la formalisation d'une gamme ayant plusieurs structures cinématiques, ainsi une contrainte entre arcs a été ajoutée d'opérations simultanées au graphe de Villeneuve. Afin d'opérationnaliser cette structure sous forme de graphe, deux types de tableaux ont été formalisé :

- Le premier tableau permet de représenter un arc ; il inclut les informations suivantes : nœuds de départ, nœuds d'arrivée, types d'opération, contrainte de simultanéité, et gammes associées.
- Le second tableau permet de représenter l'ensemble des solutions – gammes d'usinage. En effet, des gammes d'usinage peuvent être créées comme des variantes de gammes déjà existantes et en phase de génération. Ce second tableau permet de ne pas dupliquer les structures de graphes communes à plusieurs gammes, et de supporter la génération simultanée de l'ensemble des solutions.

Avant d'expliquer les étapes de l'activité "A3", certains concepts sont définis :

- **Opération** : Classiquement une opération d'usinage est référée comme une activité d'enlèvement de matière afin d'obtenir la forme désirée. Cependant, dans notre représentation graphique, un arc opération n'est pas limité aux opérations d'usinage. Elle englobe toute activité qui engage un temps, est contribue à la réalisation finale de la pièce, par exemple: les opérations d'usinage, les opérations de changement d'outil, les opérations de changement de broche, les opérations de rotation de la pièce, les opérations de changement de postes, …
- **Structure** : Une structure est un ensemble de modules cinématiques permettant le déplacement d'un ou plusieurs éléments broches + outils.
- **Postes** : Un poste d'usinage est élément du RMS composé d'une ou plusieurs structures parallèles, où des opérations d'usinage sont réalisées sur la pièce fixe. Un poste peut être assimilé à une RMT. Un poste peut inclure un module de retournement de pièce.

3.4.2. Etape 0

Objectif :

Initialisation des variables. Créer une première gamme, avec un premier poste, …

Traitement :

- Initialisation des différentes listes et des différents tableaux :
    - Les opérations sont triées selon leurs antériorités et postériorités.
    - L'opération ayant aucune antériorité et le maximum de postériorité est sélectionnée.
    - Les opérations sont triées par similarité de direction broche avec l'opération sélectionnée.
    - Les opérations sont triées par direction de broche alternante à l'opération sélectionnée.

  - Les opérations sont triées par similarité de type opération avec l'opération sélectionnée.
  - Les opérations sont triées par similarité des axes avec l'opération sélectionnée.
- Création de la première gamme, du premier poste et de la première structure.

Illustration :

Lors de cette étape, la première gamme, le premier poste, … sont instanciés. Les classifications et regroupements des opérations sont effectués. Comme illustration, une des classifications « précédence ranking » de cette étape est montrée en Figure 60 : Opérations {1, 15, 20 et 21} sont avec précédence « zéro ».

3.4.3. Etape 1

Objectif :

Cette première étape vise à identifier pour chaque gamme déjà générée quelles sont les opérations réalisables à cette itération et de compléter celles-ci. Il s'agit de lister parmi les opérations non réalisées, celles n'ayant aucune « antériorité », et de sélectionner celle qui a la « postériorité » maximale.

Traitement :

Les différentes procédures qui s'appliquent lors de cette étape sont :

- tri des opérations non instanciées en fonction des antériorités et sélection de celles qui ont une antériorité nulle,
- sélection de la (des) opération(s) à la postériorité maximale parmi celles sélectionnées à la procédure précédente,
- instanciation de l'opération associée à une gamme, un poste et une structure,
- mise à jour pour chaque gamme de la liste des opérations déjà instanciées et des tableaux résultant des traitements de l'étape 0.

Illustration :

Dans le cas de la pièce CAI, la première étape identifie les opérations {1, 15, 20 et 21} avec zéro précédence et l'opération {1} comme opération ayant la postériorité maximale. Le déroulement de cette étape sur pièce CAI est montré en Figure 62.

3.4.4. Etape 2

Objectif :

La deuxième étape consiste à identifier pour chaque gamme déjà générée les opérations aux antériorités nulles et qui sont similaires à l'opération instanciée à la première étape, et de créer des gammes alternatives avec ces opérations – la notion de similarité signifie que la cinématique nécessaire à la réalisation des opérations ainsi que la direction d'accessibilité des entités sont identiques.

Traitement :

Dans cette étape se déroulent les processus suivants :

- sélection des opérations de direction de broche, d'axes, et de type identique à celle instanciée à l'étape 1 parmi celles à antériorité nulle,
    - si ensemble vide : passage à l'étape suivante,
    - si ensemble non vide : création de nouvelles gammes alternatives avec affectation des opérations.

Illustration :

Le déroulement de cette étape sur la pièce CAI est montré en Figure 64, Figure 65, Figure 66 et Figure 67. Les classifications sont par type d'axe, même direction de broche et même type d'opération.

3.4.5. Etape 3

Objectif :

L'objectif de cette troisième étape est d'explorer les solutions déjà créées en étudiant les possibilités de réalisation d'opérations en simultanée aux opérations déjà instanciées aux étapes 1 et 2 par une ou plusieurs structures parallèles et ainsi créer des gammes alternatives avec ces opérations réalisées par de nouvelles structures.

Traitement :

Nous proposons de définir le critère de sélection comme étant une direction d'accessibilité différente par rapport aux opérations précédemment instanciées.

- sélection des opérations qui ont une direction de broche alternative par rapport aux opérations instanciées aux étapes 1 et 2 sur le poste considéré parmi les opérations à antériorité nulle,
    - si ensemble vide : dans ce cas passage à l'étape suivante, en effet aucune opération n'est possible,
    - si l'ensemble non vide, division en groupe d'opérations de même direction de broche et de même type d'opération ; création d'une nouvelle gamme en copiant la précédente et en instanciant une ou plusieurs nouvelles structures (en fonction du nombre de groupe) et les groupes d'opérations.

Illustration :

Cette étape est illustrée sur la pièce CAI. Le résultat : tableau de « groupe _ broche _ alternative » est montré en Figure 69. L'ensemble {5, 6, 10, 11,16, 20 et 21} est identifié. Les autres critères réduisent l'ensemble à deux groupes : {15} et {20-21}. Nous avons fait l'hypothèse que les opérations similaires sur des entités identiques seront réalisées en parallèle. Cette contrainte peut être supprimée si nécessaire. Le déroulement de cette étape sur la pièce CAI est montré en Figure 70.

3.4.6. Etape 4

Objectif :

Le but de cette quatrième étape est de générer les solutions alternatives possibles via un changement d'outil. Les opérations alors sélectionnées seront de même cinématique et de même direction d'accessibilité que les opérations déjà instanciées sur la poste.

Traitement :

Les sous étapes sont :

- Mise à jour des tableaux créés à l'étape 0, avec la suppression des opérations déjà instanciées,
- sélection parmi le nouvel ensemble d'opérations à antériorité nulle des opérations qui ont même direction de broche et même axes que celles déjà instanciées sur le poste et sur chaque structure,
    - si ensemble vide : passage à l'étape suivante,
    - si ensemble non vide :
        - subdivision des opérations en groupe de même type d'opération,
        - création d'une nouvelle gamme en copiant la précédente et instanciation d'une opération de changement d'outil et d'un groupe d'opérations.

Illustration :

Parmi les deux gammes possibles (Figure 70) générées en étape 3, nous avons choisi d'illustrer sur le cas {1, 20-21}. Le nouvel ensemble de d'opération antériorité zéro est {2,15}. L'ensemble {2, 15} satisfait les autres critères de broche direction similaire et même mouvement des axes. En effet, une fois l'ébauche du plan effectuée, un changement d'outil peut être opérer et ainsi effectuer la finition du plan (Figure 72).

3.4.7. Etape 5

Objectif :

Cette étape génère des alternatives possibles des gammes existantes (étape 3) via une opération de retournement de la pièce ; le critère permettant d'identifier ces opportunités de gammes alternatives est l'existence d'opération de même nature que les opérations identifiées dans les deux étapes précédentes et dont la direction d'accessibilité de l'entité est différente.

Traitement :

Les sous étapes sont :

- Mise à jour des tableaux créés à l'étape 0, avec la suppression des opérations déjà instanciées,

- sélection parmi le nouvel ensemble d'opérations à antériorité nulle des opérations qui ont une direction de broche alternative et même type cinématique que celles déjà instanciées sur le poste et sur chaque structure, ,
    - si ensemble vide : passage à l'étape suivante,
    - si ensemble non vide :
        - subdivision des opérations en groupe de même direction de broche et de même nature,
        - création d'une nouvelle gamme en copiant la précédente et instanciation d'une opération de retournement de pièce et du groupe d'opérations.

Illustration :

Après l'étape 4 illustrée ci-dessus, le nouvel ensemble d'antériorité nulle est {5, 10 et 16}. L'ensemble {5, 10} satisfait les autres critères de broche direction alternative et même type cinématique déjà instanciés sur le poste et la deuxième structure (Figure 74).

3.4.8. Etape 6

Cette étape a pour but de réaliser un tri des gammes déjà créées à la sortie des boucles des étapes 4 et 5. Celle-ci renvoie les gammes à l'étape 1 pour continuer leur génération sur un nouveau poste, et elle renvoie ces mêmes gammes aux étapes 4 et 5 pour l'étude de gammes alternatives par changement d'outil ou retournement de la pièce sur le poste considéré. Pour cela, l'algorithme teste si un ajout d'opération a été effectué, si une gamme revient à l'étape 6 avec les mêmes opérations (sans ajout), sa génération est arrêtée sur ce poste. Ainsi les bouclages successifs des étapes 4, 5 et 6, permettent de réaliser le schéma en Figure 75.
Ainsi l'ensemble des possibilités sur un poste est exploré, le changement de poste est justifié.

Illustration :

Etape 6 est appliquée sur une des gammes générée jusqu'à l'étape 5. Dans la boucle 4-5, l'étape 4 ne retourne aucune nouvelle gamme et l'étape 5 génère une nouvelle opération {16}. Dans ce cas, une première solution complète a été trouvée (Figure 76).

3.5. Discussion

L'algorithme de conception a été appliqué avec succès sur 3 pièces différentes. Pour la pièce CAI, plus de 80 solutions différentes ont été générés dont le panel va de toutes les opérations sur un seul poste à chaque poste ayant seulement une opération d'usinage. Le premier scénario a été illustré avec un exemple dans la section précédente. La configuration de la Figure 77 a deux structures parallèles, la première comportant deux axes et seconde un axe. Les deux structures ont les modules de changement d'outils, de broches et de rotation pièce. L'autre solution extrême comporte cinq postes. Cette configuration a deux structures deux axes et cinq structures un axe (Figure 79).

3.6. Conclusion

Les approches 'traditionnelles' de conception de systèmes de production ne sont plus applicables sur ce nouveau type de systèmes reconfigurables, les critères de génération des gammes ayant été modifiées. Ce nouveau concept de systèmes de production nécessite une nouvelle approche intégrant des critères de développement spécifiques. Le gammiste ne vise plus à réduire le nombre de posage, mais à optimiser les critères de temps et de coût pour la fabrication de la pièce. Ce travail s'intègre dans le cadre de conception basé sur la méthode FBS quant à la conception d'un système de production reconfigurable.

Le processus de génération des gammes d'usinage et des configurations cinématiques est basé sur les entrées fonctionnelles : la famille de produit ou le groupe de pièces à réaliser. Ce travail présente le développement d'un algorithme itératif de génération de toutes les alternatives de gammes viables. Cet algorithme ainsi que son implémentation informatique ont été testés sur 3 pièces afin de les valider.

Nous émettons deux critiques relatives à cette approche :

- Lors de la génération des gammes et structures, les contraintes liées au posage de la pièce ne sont pas intégrées.
- Lors de la génération des gammes et structures, les contraintes liées aux collisions entre les structures ne sont pas intégrées.

Ces deux remarques nécessiteront des évaluations des différentes gammes générées par rapport à ces contraintes.

4. Chapitre 4 : Une approche pour l'évaluation des solutions pour la conception d'un système de production reconfigurable.

L'évaluation des solutions de conception nécessite la définition de critères. Ces critères peuvent être divisés en deux domaines : statique et dynamique. L'évaluation statique d'un système de la production consiste en la fiabilité, maniabilité, ergonomiques, sécurité, …. Pour les critères liés à la reconfigurabilité, à l'étendue des pièces réalisables, … O. Garro a proposé les critères d'évaluation dynamiques suivant la productivité, la flexibilité et le coût (Garro, 1992). La flexibilité dépend de l'axe temporel et elle peut être divisée suivant trois niveaux :

- à court terme, la flexibilité concerne le niveau opérationnel, comme l'affectation en dynamique d'une pièce à une autre machine,
- à moyen terme, elle concerne le niveau tactique tel le changement du mode de réalisation,
- à long terme, elle concerne le niveau stratégique de type : changement de production.

Ainsi, O. Garro a proposé la notion d'entropie pour caractériser cette flexibilité.

Les critères de sélection d'une gamme de fabrication sont : le coût (Sormaz, 2003), les temps ; le nombre de posages, le nombre d'opérations, la qualité…. Ces critères mesurent la différence entre la performance attendue et la performance réalisée. Dans le chapitre 2, nous avons proposé un cadre de conception basée sur l'approche FBS permettant ces mesures. Ce cadre définit les liens entre les activités de conception et les solutions de conception. Ces liens sont réalisés via les indicateurs de performance (PI). Les quatre critères principaux proposés sont : l'étendu de la famille de produit, la qualité, les temps et les coûts (Figure 80).

4.1. Evaluation

La structuration proposée dans le chapitre 2 repose sur l'approche de la conception axiomatique qui a pour but essentiel la mesure de la qualité d'un système en termes d'aptitude à la reconception et à la mise en oeuvre. Pour juger de la qualité d'une conception, Suh prend en considération deux axiomes : l'axiome d'indépendance et l'axiome d'information. L'axiome d'indépendance stipule qu'une conception optimale ne doit pas entrainer de couplage dans la réalisation des fonctions (indépendance) au travers de la structure. Une conception acceptable doit éviter que l'amélioration d'une fonction ne puisse se faire sans la dégradation d'une autre. L'axiome d'information stipule qu'une conception est globalement optimale si elle nécessite un minimum d'information. L'information dont il est question ici représente les instructions nécessaires à assurer l'adéquation entre le niveau de satisfaction attendu d'une fonction et la performance fournie par le système.

Suite à cette structuration, les dépendances des quatre principaux critères ont été identifiées et décomposées (Figure 80). Ainsi, ces quatre indicateurs de performances peuvent être évalués dans une manière hiérarchique ; les approches d'évaluation de ceux-ci sont détaillées dans la suite de ce chapitre.

4.1.1. Etendu de la famille de produit

L'étendu de la famille de produit représente l'ensemble des variantes des entités réalisables, les intervalles des valeurs réalisables des paramètres de ces entités, … Dans le chapitre 3, les solutions sont générées pour un groupe de pièces représentatif de cette étendu. Chaque solution satisfait la condition de réalisation de la famille de produit. Cette affirmation est à modérer car les contraintes liées au posage et les contraintes liées aux collisions n'ont pas été prises en compte. Il est donc nécessaire d'évaluer la faisabilité de chaque gamme :

- le posage doit être matériellement réalisable : Si la détermination des surfaces d'appui et de bridage ne peut pas assurer le maintien et la mise en position de la pièce, alors la gamme et la configuration cinématique ne sont pas capables.
- les collisions doivent être détectées. Dans ces travaux de thèse (Aladad 2009), Aladad utilise le logiciel DELMIA afin de valider la cinématique d'une machine de production.

4.1.2. Qualité

La qualité représente la garantie de la conformité du produit. Si les défauts de fabrication de la pièce sont au-delà des tolérances exigées la gamme et la configuration cinématique ne sont pas capables.

L'évaluation de ce critère vise à prédire le comportement probable du système de production suivant la gamme envisagée via des simulations. Ces simulations permettent de prendre en compte le cumul des défauts de fabrication, cette démarche n'est pas encore intégrée dans les systèmes de génération de gamme (Tichadou, 2005). Pour ce faire, il est nécessaire d'étudier les possibles sources de ces défauts d'usinage, leur contribution à la qualité et de leur effet sur les aspects fonctionnels du produit.

Dans le cas de la qualité dimensionnelle et géométrique, les différentes approches de la simulation d'usinage, qu'elles soient unidirectionnelles ou tridimensionnelles, utilisent des modèles de défauts géométriques. Nous pouvons citer les travaux de P. Bourdet (Bourdet, 73(a), Bourdet, 73(b)), de F. Villeneuve et O. Legoff (Villneuve, 2001), de S. Tichadou (Tichadeau, 2005) …

Cette évaluation sera détaillée dans le paragraphe 4.2.

4.1.3. Coûts et Temps

Les coûts représentent les charges ou dépenses supportées pour la production d'un produit. Les temps représentent les durées de chaque opération ou activité (activité de production, activité de préparation du système, activité de reconfiguration, …).

Les estimations des coûts de fabrication peuvent être réalisées par différentes approches : les méthodes paramétriques, analytiques et analogiques.

Les méthodes par analogie reposent sur l'évaluation du coût d'un nouveau produit à partir de ceux déjà réalisés. Ces derniers sont décrits à l'aide de paramètres jugés discriminants et pertinents (comme la morphologie, la qualité, les dimensions,…) qui permettront également de décrire le nouveau produit dont on veut une estimation du coût. Cette approche est similaire aux approches de génération de gammes par variante.

Par méthodes paramétriques sont regroupées toutes les méthodes qui permettent l'évaluation du coût en se basant sur la connaissance de relations mathématiques le reliant aux paramètres quantifiables du produit tels que le volume, la dureté, le temps, etc.

On regroupe sous la bannière des méthodes analytiques l'ensemble des solutions qui, pour estimer le coût d'un produit s'appuient sur les opérations et activités nécessaires à son cycle de vie (que ce soit son processus de conception, de fabrication, d'exploitation ou de fin de vie).

Dans notre cas, les solutions générées via l'approche algorithmique du chapitre 3 sont formalisées sous la forme d'un ensemble d'activités ou opérations ordonnées avec les modules cinématiques associés. Les approches analytiques s'appuient sur cette décomposition en activité. De ce fait, nous avons retenu l'approche « Activity Based Costing (ABC) » (Park, 1995; Ioannou, 1999 ; Ong, 1993).

L'identification des activités et des ressources (modules cinématiques) faite, l'approche ABC revient à quantifier trois inducteurs afin de faire émerger le coût :

- Inducteur de ressources : permet de ventiler les ressources entre les différentes activités. Cette répartition peut prendre la forme, par exemple, du temps consacré à chaque activité, ou la quantité de matière première, ...
- Inducteur de coût : facteur influençant le niveau de performance de l'activité et sa consommation de ressources associées.
- Inducteur d'activité : Cet inducteur permet de répartir les coûts des activités entre les différents produits.

$$Coût = \sum_i (Ind_i^A .\ Ind_i^C . Ind_{i,j}^R .Cout_j)$$

Ind_i^A : Inducteur d'activité i

Ind_i^C : Inducteur de coût de l'activité i

$Ind_{i,j}^R$: Inducteur de Ressource reliant l'activité i à la ressource j

$Cout_j$: Coût de la ressource j

L'ensemble de ces inducteurs est identifiable pour chaque arc du graphe des solutions.

De plus, nous pouvons adopter la décomposition des coûts et des temps proposée par Feng (Feng, 2000). Chaque activité implique des coûts et temps d'utilisation de quelques ressources :

$$C_m^0 = \sum_{i=1}^{N} C_{activité}^i$$

$$= \sum_{i=1}^{N} \left(C_{u\sin age}^i + C_{setup}^i + C_{manutention}^i + C_{load-unload}^i + C_{idling}^i + C_{overhead}^i \right)$$

C_m^0 est le coût de fabrication de la pièce sans prendre en compte le coût des risques associés

i est un indice

N est le nombre total des activités de fabrication appliquées sur la pièce

$C^{i}_{activité}$ est le coût de fabrication de l'activité *i*

$C^{i}_{usinage}$ est le coût d'usinage de l'activité *i*

C^{i}_{setup} est le coût de l'activité *i*

$C^{i}_{manutention}$ est le coût de transfert de l'activité *i* (ex. transférer les outils et les matériels)

$C^{i}_{load\text{-}unload}$ est le coût de montage/démontage de l'activité *i*

C^{i}_{idling} est le coût de perdre de temps de l'activité *i*

$C^{i}_{overhead}$ est le coût des frais généraux de l'activité *i*.

Le coût d'usinage est donné par l'équation :

$$C^{i}_{usinage} = C^{i}_{équipement} + C^{i}_{main\ d'oeuvre} + C^{i}_{matérial} + C^{i}_{outil}$$

4.2. Simulation géométrique de processus d'usinage

Dans ce paragraphe, nous nous sommes focalisées sur l'évaluation des caractéristiques géométriques et dimensionnelles de la chaîne cinématique du système de fabrication. Chaque configuration possède un ensemble particulier de caractéristiques géométriques. Ainsi, il faut avoir une méthode pour valider les configurations proposées.

Une approche, permettant de formaliser mathématiquement les spécifications et les incertitudes de fabrication, et d'exprimer le comportement géométrique attendu est l'approche par Δl développée par P. Bourdet (Bourdet 1975). Cette approche propose de quantifier les cotes fabriquées (Cf) à partir des cotes fonctionnelles (CF), considérées comme connues. Cette approche se compose de deux étapes majeures :

- La première consiste à établir le graphe de simulation, qui est une modélisation du processus de fabrication. Sur ce modèle, chaque surface est représentée par une colonne, et chaque repère correspond à une étape du processus de fabrication. Les croix désignent les surfaces crées et les triangles les surfaces participant à la mise en position de la pièce. Les intervalles de tolérance des cotes de simulation sont notés Δl_i pour les surfaces créées et Δl_i^j pour les surfaces de contact. L'indice i est le numéro de la surface concernée, l'exposant j est le numéro de la phase ou du repère.

- A partir de ce graphe, l'approche propose d'établir les relations formelles entre les cotes fabriquées (et leurs intervalles de tolérances Δl_i associés) pour chaque cote fonctionnelle. Puisque l'approche est basée sur une modélisation unidimensionnelle, le trajet minimal est unique. L'écriture de ces relations est alors univoque et rapide. Ces relations permettent de valider ou non la gamme d'usinage.

Cette approche a été généralisée par S. Tichadou qui a proposé l'utilisation des graphes pour formaliser la gamme d'usinage, et l'utilisation de torseurs de petit déplacement pour modéliser les défauts. Cette approche repose sur la modélisation du processus de fabrication, en mettant en évidence les relations (de contact, d'usinage et de positionnement principalement) entre les entités géométriques de la pièce et les ressources d'usinage (machine, porte pièce, et l'opération d'usinage employée). Cette modélisation permet alors l'identification des jeux et des écarts qu'il est nécessaire de formaliser sous la forme de torseurs.

Etant donné certaines similarités entre les graphes développés par S. Tichadou et les graphes proposés au chapitre 3, nous avons choisi d'adapter son approche à notre problème.

Afin de proposer un « mapping » entre les deux types de graphe, étudions les objectifs de modélisation de chacun.

La modélisation par graphe de S. Tichadou s'appuie sur le concept de la cellule élémentaire de fabrication ou un poste de fabrication qui inclut les éléments suivants :

- la machine-outil : ensemble composé de plusieurs liaisons pilotées et contrôlées pour générer des mouvements de coupe et d'avance relatifs entre la pièce et les outils ;
- le porte-pièce : assemblage, installé sur la machine outil, dont les fonctions principales sont de positionner et de maintenir la pièce ;
- la pièce à usiner : solide provenant de la phase précédente dans un état intermédiaire ;
- les outils et leurs attachements : assemblages de différents composants (arête de coupe, porte-plaquette, porte-outil, éléments de bridage, etc.) ;
- les trajectoires de travail : mouvements relatifs entre l'outil et la pièce décrivant les conditions cinématiques d'usinage, la plupart du temps matérialisés par des programmes définis dans des repères localisés dans l'espace machine.

Dans notre cas, la cellule élémentaire de fabrication inclut les éléments suivants :

- le poste (chapitre 3)
- la structure assimilable à la machine-outil : ensemble composé de plusieurs liaisons pilotées et contrôlées pour générer des mouvements de coupe et d'avance relatifs entre la pièce et les outils ; un poste peut comporter plusieurs structures exécutant des opérations en simultanée.
- le porte-pièce : assemblage mobile se déplaçant de poste en poste dont les fonctions principales sont de positionner et de maintenir la pièce durant les opérations d'usinage effectuées par les structures ;
- la pièce à usiner : solide provenant du poste précédent dans un état intermédiaire ;
- les outils et leurs attachements : assemblages de différents composants (arête de coupe, porte-plaquette, porte-outil, éléments de bridage, etc.) ;
- les trajectoires de travail : mouvements relatifs entre l'outil et la pièce décrivant les conditions cinématiques d'usinage.

Nous pouvons remarquer certaines différences entre les deux cellules élémentaires. Afin de compléter cette analyse, une étude des sources des défauts de fabrication est nécessaire. Ainsi, les sources des défauts relatives à la cellule élémentaire classique sont :

- Sur la machine-outil : les défauts structurels de liaisons tels des rectitudes de mouvement, des faux ronds, les défauts géométriques, dilation thermique, déformation machine, la résolution de déplacement, … les défauts de comportement dynamique entraînés par des conditions d'utilisation.
- Sur le porte-pièce et les outils : les défauts géométriques et dimensionnels, les erreurs de mesures de jauges, les déformations engendrées par les actions mécaniques d'usinage affectant les porte-pièce et/ou les outils (Seo, 1998) (Larue 2003).
- Sur la pièce dans son état intermédiaire : la variabilité des dimensions issues d'un lot de production lors de la phase précédente, les déformations dues aux actions mécaniques d'usinage et de maintien en position.
- Sur les trajectoires d'usinage : les erreurs de calculs de trajectoire faite en FAO.

Dans notre cas, nous pouvons ajouter les sources suivantes :

- Sur le porte de pièce : les défauts de mise en position du porte de pièce sur le poste et de retournement de l'ensemble pièce et porte pièce.
- Sur la structure : les défauts cités précédemment de la machine-outil, plus les défauts de reconfiguration de cette structure sur le poste.

Ainsi pour la modélisation via un graphe, S. Tichadou a proposé de modéliser toutes les entités d'une phase sous la forme de composants physiques. Chaque sommet du graphe représente l'état de la pièce après chaque phase. Les surfaces associées à un sommet « phase » sont les surfaces actives : surfaces d'appui ou surfaces fabriquées de la phase. Une phase est définie comme la cellule élémentaire, les éléments constituant celle-ci sont : la machine-outil, le porte-pièce, la pièce fabriquée ainsi que les opérations de fabrication. Chaque opération est définie par le volume de matière enlevé par un outil suivant une trajectoire. Une spécification géométrique sur la pièce finie est une condition interne ou externe à une phase. Elle est dite directe dans le cas où les surfaces considérées sont actives dans la même phase et transférée dans les autres cas.

Pour l'adaptation de ce graphe à la modélisation d'une gamme d'usinage réalisée sur un RMS, plusieurs concepts ont été modifiés :

- La notion de phase a été remplacée par la notion de poste,
- Le fait qu'il soit possible d'avoir plusieurs structures sur un même poste, a été modélisé par plusieurs machines dans une même phase,
- Le fait qu'il soit possible de retourner la pièce sur poste et ainsi de réaliser plusieurs entités via une même structure, a été modélisé en dupliquant la phase et en intégrant un élément « position »,

Ces modifications et plus particulièrement la dernière ont nécessitées l'ajout d'heuristiques dans le traitement de celui (le calcul des chaînes de cotes) :

- Si la structure$_i$ apparait 2 fois dans la chaine alors la deuxième occurrence n'est pas prise en compte dans le cumul des défauts,

- Si la broche$_i$ apparait 2 fois dans la chaine alors la deuxième occurrence n'est pas prise en compte dans le cumul des défauts,

- Si un seul élément position apparait dans la chaine alors cette occurrence n'est pas prise en compte dans le cumul des défauts.

Une vue générique de la représentation graphique d'une gamme est montrée dans la Figure 88. Suite à l'adaptation, il est possible d'envisager la procédure de « mapping » du graphe des solutions générées au chapitre 3 à ces graphes. Ce « mapping » est simple étant donné la similarité des concepts manipulés :

- Poste ≈ Poste,
- Opération ≈ Surface + Opération + Broche,
- Retournement de pièce ≈ Position,
- Ensemble d'opérations en série sur un poste ≈ Structure

A partir des graphes, une approche de la simulation unidirectionnelle ou tridimensionnelle d'usinage est possible sous un aspect formel, basé sur une modélisation des défauts géométriques par les Δl ou les torseurs de petit déplacement. En reprenant le graphe de représentation compacté, on peut dresser la liste des types de Δl ou torseurs qui caractérisent les écarts géométriques « à cause » ou « entre » les différents éléments : Δl Opération, Δl Broche + Outil, Δl Structure, Δl Position, et Poste.

Chaque spécification géométrique contraint les défauts de position ou d'orientation relatifs entre deux surfaces de la pièce. Grâce aux graphes de représentation, l'expression du Δl resultant associé chaque spécification est la somme des Δl qui se trouvent sur le chemin entre les deux surfaces. Il suffit d'écrire chaque fermeture de chaîne pour trouver les différents composants de Δl pour formuler la condition :

$IT_{specif} \geq \Delta l_{résultant} = \sum \Delta l_{\in Chaine}$

La solution présentant l'ensemble des opérations d'usinage effectué à un seul poste a été choisi pour illustrer la simulation par Δl. La structure correspondante pour la gamme sélectionnée est montrée en Figure 90. Il a deux structures parallèles, chaque une ayant plusieurs changements d'outil et de broche, et ayant un retournement de pièce. La configuration est illustrée en Figure 91. 11 spécifications entre surfaces ont été considérées (Figure 92) (le dessin de définition fonctionnel est en Annexe E). En utilisant les heuristiques et la composition des Δl, les relations ci-dessous sont définies et calculées :

$ITC_{P22-P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Structure2} + \Delta L_{Broche6} + \Delta L_{Tooling22}$
$= 0.002 + 0.003+ 0.004 +0.004 + 0.004 +0.004 + 0.003 +0.002$
$= 0.026$

$ITC_{P32-P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Structure2} + \Delta L_{Broche6} + \Delta L_{Tooling32}$
$= 0.026$

$ITC_{P42-P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + \Delta L_{Position\ 1} + \Delta L_{Position\ 3} + \Delta L_{Structure2} + \Delta L_{Broche7} + \Delta L_{Tooling42}$
$= 0.026$

$ITC_{P7-P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + + \Delta L_{Structure2} + \Delta L_{Broche3} + \Delta L_{Tooling7}$
$= 0.018$

$ITC_{P8-P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + + \Delta L_{Structure2} + \Delta L_{Broche3} + \Delta L_{Tooling8}$

$= 0.018$

$ITC_{P7\text{-}P22} = \Delta L_{\ Tooling7} + \Delta L_{\ Broche3} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 1} + \Delta L_{\ Position\ 2} + \Delta L_{\ Broche6} + \Delta L_{\ Tooling22}$

$=0.022$

$ITC_{P7\text{-}P32} = \Delta L_{\ Tooling7} + \Delta L_{\ Broche3} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 1} + \Delta L_{\ Position\ 2} + \Delta L_{\ Broche6} + \Delta L_{\ Tooling32}$

$= 0.022$

$ITC_{P8\text{-}P22} = \Delta L_{\ Tooling8} + \Delta L_{\ Broche3} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 1} + \Delta L_{\ Position\ 2} + \Delta L_{\ Broche6} + \Delta L_{\ Tooling22}$

$= 0.022$

$ITC_{P8\text{-}P32} = \Delta L_{\ Tooling8} + \Delta L_{\ Broche3} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 1} + \Delta L_{\ Position\ 2} + \Delta L_{\ Broche6} + \Delta L_{\ Tooling32}$

$= 0.022$

$ITC_{P42\text{-}P22} = \Delta L_{\ Tooling42} + \Delta L_{\ Broche7} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 3} + \Delta L_{\ Position\ 2} + \Delta L_{\ Broche6} + \Delta L_{\ Tooling22}$

$= 0.022$

$ITC_{P42\text{-}P32} = \Delta L_{\ Tooling12} + \Delta L_{\ Broche7} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 3} + \Delta L_{\ Position\ 2} + \Delta L_{\ Broche6} + \Delta L_{\ Tooling32}$

$= 0.022$

Cette démarche a été effectuée sur d’autres solutions. Elle permet de comparer ces solutions d’un point de vue Qualité – respect des spécifications.

4.3. Conclusion

La sélection des solutions générées au chapitre 3 nécessite la définition de critères et les approches d’évaluation de ceux-ci. L’étendu de la famille de produit, la qualité, le coût, et le temps sont les principaux critères à mesurer. Pour chacun de ces critères, des approches d’évaluation ont été identifiées à partir d’une recherche bibliographique. Nous pouvons citer : l’entropie proposé par O. Garro pour l’étendu de la famille de produit, l’approche ABC pour les coûts.

Dans le cas du critère qualité, les approches classiques comme les Δl ne sont pas directement utilisables pour la simulation d’une gamme sur un RMS. L’architecture d’un RMS présente des structures en parallèle. Une adaptation des graphes générées au chapitre 3 a été proposée afin d’utiliser les approches de simulation développées par S. Tichadou.

Ces travaux pourront être complétés par :

- l’analyse de la robustesse et la sensibilité des indicateurs de performance définis,
- l’étude de l'agrégation des indicateurs de performance.

5. **Conclusion et perspectives**

Ces travaux de thèse se positionnent dans le domaine de conception du système de production reconfigurable. Ils visent à établir un lien entre le niveau stratégique et le niveau opérationnel, et à proposer des outils de conception au niveau opérationnel ; ils contribuent à répondre à :

« Comment optimiser la conception du processus d'usinage et du système de production reconfigurable en tenant compte des interactions entre le processus et les ressources, des contraintes technologiques imposées par la pièce à fabriquer ? »

La démarche que nous avons mise en œuvre pour atteindre cet objectif se décompose de la façon suivante :

- Etude bibliographique relative aux démarches et outils de conception des systèmes de production,
- Formalisation des besoins et problématiques de nos travaux,

  Les travaux relatifs aux méthodologies de conception des systèmes de production sont orientés vers deux directions : une au niveau stratégique visant à optimiser le retour sur investissement, la seconde au niveau opérationnel visant à optimiser la structure et la partie commande. Nous pouvons remarquer un manque de connections entre ces deux directions.

  Les approches existantes de génération de gammes d'usinage nécessitent des connaissances sur les architectures des systèmes de production utilisables ; de même, les approches de conception de l'architecture de système de production nécessitent la connaissance des gammes d'usinage à réaliser sur celui-ci. Nous sommes confronté à un paradoxe : la conception de A nécessite des connaissances sur B et « vice et versa ».

  Ces deux constats ont motivé nos travaux.

- Définition d'un cadre de conception permettant le lien entre le niveau stratégique et le niveau opérationnel,

  Basé sur les travaux de D. Cochran utilisant l'approche Axiomatic design pour formaliser la conception d'un système de production au niveau stratégique, nous avons proposé une adaptation de l'approche FBS pour la conception de celui-ci au niveau opérationnel, et des connections entre ces deux niveaux par la structuration des indicateurs de performances et l'utilisation des principes d'Axiomatic Design.

- Définition d'une démarche algorithmique permettant d'explorer les solutions au niveau opérationnel (co-conception des gammes d'usinage et des configurations cinématiques associées du RMS),

  Basé sur les travaux de génération de gamme d'usinage (entité d'usinage, carte de visite, matrice d'antériorité,…), nous avons proposé une approche algorithmique de génération des gammes d'usinage en explorant l'ensemble des possibilités offertes par les RMS : plusieurs structures cinématiques usinant en simultané, … et en s'affranchissant de l'objectif nombre minimal de phases. La génération est supportée par une structuration en graphe des solutions générées. Des gammes d'usinage peuvent être créées comme des variantes de gammes déjà existantes et en phase de génération. Cette démarche générative peut être assimilable à un problème de satisfaction de contraintes dynamiques - le nombre de variables et de contraintes dépendant des valeurs prises par certaines variables. Les configurations cinématiques nécessaires pour chaque opération d'usinage sont identifiées. Cette démarche a été implémentée, puis validée sur 3 pièces du domaine de l'automobile.

- Définition des procédures d'évaluation des solutions générées,

  Basé sur le cadre défini dans le chapitre 2 et sur une étude bibliographique, nous avons proposé pour chaque critère d'évaluation une ou plusieurs approches afin de définir et quantifier celui-ci. Une attention plus particulière a été déployée pour le critère Qualité, les approches existantes nécessitant une adaptation afin de traiter la simulation des défauts à partir des graphes générées dans le chapitre 3. Une adaptation des graphes de S. Tichadou et l'utilisation de la simulation par Δl permettent la validation ou non des gammes générées.

Une vue panoramique sur la conception algorithmiques de RMS est montré dans la Figure 96.

Nous émettons des critiques relatives à cette proposition :

- Lors de la génération des gammes et structures, les contraintes liées au posage de la pièce n'ont pas été intégrées.
- Lors de la génération des gammes et structures, les contraintes liées aux collisions entre les structures n'ont pas été intégrées.
- La robustesse et l'agrégation des indicateurs de performance pour l'évaluation et la sélection des solutions n'a pas été traité.
- La validation du cadre de conception proposé dans le chapitre 2 n'a été expérimentée qu'au niveau opérationnel.

Ces critiques ouvrent différentes perspectives à ces travaux. Il est très important d'y ajouter comme perspective le couplage de cette approche d'exploration des solutions avec l'optimisation du système de production d'un point de vue logistique (par exemple les travaux d'A. Dolgui).

En dernier point, ces travaux qui au départ se focalisait sur la conception de système de production reconfigurable, ont abouti à la co-conception de processus d'usinage reconfigurables et de systèmes de production reconfigurables. Ce point n'a pas encore été exploité, il nous semble pertinent de le considérer lors de la reconfiguration d'un système existant pour la fabrication d'un nouveau produit : Quelle est la gamme et quelle est la configuration minimisant l'activité de reconfiguration ?

Version Anglaise

Introduction

Introduction

In the recent times, there has been a lot of development and expansion in the different manufacturing system paradigms. The reductions in demand, rapid evolution of products have made the new paradigm of Reconfigurable Manufacturing System appear. In terms of capability and flexibility, it finds itself in between the two previous types i.e. Flexible Manufacturing Systems and Dedicated Manufacturing Systems.

This new advancement requires a design methodology that responds to the question:

How to optimize the design of the manufacturing processes and reconfigurable manufacturing system while taking into account the interactions between the processes and resources, the technological constraints imposed by the part to be manufactured ?

A lot of work has been carried out at the “Engineering research centre for reconfigurable manufacturing systems” at the University of Michigan, Michigan, USA. Their work has demonstrated future trends towards the standardisation of parts and machine modules in all aspects of reconfiguration. Among the aspects being researched upon are: system level reconfiguration, machine level reconfiguration, reconfiguration of the machining processes, control system reconfiguration… The production system can be constituted of machine tools, weather independent or regrouped based on their capability for a small, medium or large series production line.

This thesis report is written in four chapters.

Chapter 1, allows us to position ourselves with respect to the general concepts of RMS and existing works in the domain. A literature review has been carried out by focusing on dedicated, flexible and reconfigurable manufacturing systems. Also a synthesis of different existing works in the domain of the design of reconfigurable machine tools is given

In chapter 2, a design framework for the design of reconfigurable manufacturing system has been proposed. Axiomatic design approach has been deployed for the design of manufacturing in the context of lean manufacturing. We have identified the need to have a link between the strategic and operational level. In this chapter we have proposed a supplementary domain i.e. Performance domain, which is characterized by performance indicators. Performance indicators allow forming a link between the design activities (explained in the context of lean manufacturing) and the physical solutions (explained in this work). We have coupled the axiomatic design approach with that of Function-Behavior-Structure approach for the evaluation of these performance indicators. The development and application of the design approach is oriented towards the machining operations (milling, axial drilling operations …). The design process is divided into three major domains: functional domain represented by the geometrical specifications; process domain represented by machining operations, their machining sequences and process plans; structural domain characterized by the kinematic configurations of the machine architecture.

Chapter 3 attempts to address the problem of generation of process plans and structural configurations of RMS. We have developed an algorithmic approach that allows creating a link between the functions that we want to achieve and the structure that will realize these functions. The passage is done by generation of the system behavior characterized by the operations (machining, tool change, post change …). This algorithm is validated on 3 automobile parts. The development and processing of this algorithm is done in VBA with excel as interface.

Chapter 4 focuses on the analysis of the evaluation of the generated design solutions. The selected evaluation criteria are: quality, range of product family, time and cost. Among the set of criteria, the one related to quality (already defined as a performance indicator chapter 2) is discussed in detail. Quality is defined in terms of satisfaction of geometric tolerances. We proposed a set of heuristics allowing the transfer of graphs generated in chapter 3 in graphs supporting the analysis of quality. The "Internal Tolerance condition (ITC)" of each solution in the form of graphs is calculated.

The conclusion presents a synthesis of the work carried out and allows us to propose future research objectives and directions. The increase in the level of reconfiguration from the structural domain to the process domain is discussed. The need for carrying a multi – criteria evaluation along with other evaluation criteria like time, cost… is highlighted. Aggregation of the performance indicators is also proposed.

Chapter 1

A Review of Reconfigurable Manufacturing Systems

Chapter 1

A Review of Reconfigurable Manufacturing Systems

Reconfigurable Manufacturing Systems are the recent addition in the series of different types manufacturing system. Their design is based on the concept of part family, which they are required to manufacture. In this chapter we have compared the existing manufacturing paradigms based on the key technological characteristics. Principles of Reconfigurable Systems, along with the key enabling technologies are explained. A synthesis based on the concepts of reconfigurability and flexibility is carried out. A literature review of the existing work in the domain of reconfigurable systems in general and reconfigurable machine tool in particular is carried out. The need for a design methodology which takes into account the basic design principles of reconfiguration and the technological constraints imposed by the part family is highlighted.

Changing Manufacturing Paradigms

Manufacturing can be thought of as a system in which product design is the initial stage, and the delivery of finished products to the market is the final output (Koren, 1999). Manufacturing can be subdivided into manufacturing processes, which alter the form, shape and/or physical properties of a given material; manufacturing equipment used to perform manufacturing processes; and the manufacturing systems, which are the combination of manufacturing equipment and humans, bound by a common material and information flow. Thus the choice of a manufacturing system represents the objectives of the enterprise.

Customer and market requirements are not only subject to rapid changes but also they require the companies to deliver a product that respects the requirements of low price, high variety, and good quality. The strategies used to respond to these conflicting and tough requirements include decentralization, manufacturing of intermediate products, automation, improvement in logistics, and development of new manufacturing systems…). Our work is concerned with the development of new innovative manufacturing systems having capability to respond to market requirements.

A manufacturing system can be constituted of isolated numerically controlled machine tools for customized production or grouping together machine cells for an automated transfer line for mass production.

Flexible manufacturing systems (FMS) developed in the 80’s were expensive and often under used in terms of their capability as compared to the dedicated manufacturing lines (DML), which have a high productivity but are rigid towards further evolution. The rapid evolution of the design and launching of new products, the need to fabricate the products of high quality and at reasonable price has enhanced the need for a quick and adaptable manufacturing system. To grasp the short window of opportunity along with the need to reduce cost and the time because of design and product volume changes, the reconfigurable manufacturing system (RMS) concept was introduced.

In terms of design, RMS has a modular structure (software and hardware) that allows the ease of reconfiguration as a strategy to adapt to market demands. Modular machines and open- architecture controllers are the key enabling technologies for

RMS, and have the ability to integrate / remove new software/hardware modules without affecting the rest of the system. This offers RMS the ability to be converted for the production of new products, to quickly adjust to exact capacity requirements as the market grows and product changes, and to be able to integrate new technologies. RMS not only combines the high throughput of DMLs with the flexibility of FMS, but also is able to react to changes quickly and effectively

However, research regarding the design of reconfigurable machine tools (RMTs) and (RMS) has been going on in United States, under the supervision of Pr. P.Koren since 1998 at the University of Michigan. The future trend towards the standardization of the components as well as modules for reconfiguration has been demonstrated. Among the most important aspects discussed are: the reconfiguration of manufacturing system, machine tools, processes, control system…

In Germany, the project "METEOR 2010" (Multi Technology based Reconfigurable Machine Tool 2010 (Meteor2010, web). An approach for the generation of machine tool configuration using reconfigurable process plans have been proposed by H. ElMaraghy. The concept of modular machine tools have been addressed before the concept of reconfigurability became popular. Garro (Garro, 1992) in his thesis under the direction of P. Martin worked on the design of operational aspect of modular machines having parallel architectures.

1 Objective

This chapter is written with an aim to carry out an in-depth literature review of the existing paradigm of reconfigurable manufacturing systems. Also it reviews the basic design considerations to be taken into account. It attempts to highlight:

- the state of art and the need for reconfigurable manufacturing systems (RMS),
- design parameters for the design of a RMS,
- existing work in the domain of RMS and its most important sub component reconfigurable machine tool (RMT).

All these review areas are discussed with reference to the overall objective of this thesis i.e. development of a methodology for the design of RMS.

The problem areas associated with the design and implementation of a RMS are: global design of a RMS, design of each reconfigurable machine tool (RMT), design of the control system, validation and definition of rules governing reconfiguration. Most of the existing work is oriented towards RMS design at the strategic level, giving out the design activities involved. There is very less advancement at the operational level of RMS design which includes the number of RMTs required and detailed kinematic design for each of them. More importantly the link between the strategic and operational level is missing.

In our work, we have concentrated on the technological aspects of a RMS along with providing the connection between strategic and operational level through performance indicators (Chapter 2 and Chapter 3). They are the factors that are directly linked to: range of product family, quality, cost and time (Chapter 4); interaction between machining features and their realization for a product family. We focus in particular on the development of design methodology and the definition of parameters for evaluation of these design solutions.

The development and application of the design approach is oriented towards the machining operations (milling, axial drilling operations …). The design process is divided into three major domains: functional domain represented by the geometrical specifications; process domain represented by machining operations, their machining sequences and process plans; structural domain characterized by the kinematic configurations of the machine architecture.

2 Manufacturing Systems

A production system is defined as a set of successive transformations in passing from the initial state to its final state (Dano, 1966). Machining operations are one of the main agents that cause these transformations. Our work is oriented towards the generation of kinematic machine configurations with particular reference to machining. According to ElMaraghy (ElMaraghy, 2005), manufacturing systems can be classified into three majors groups based on their productivity and flexibility.

- Dedicated Manufacturing Lines (DML)
- Flexible Manufacturing Systems (FMS)
- Reconfigurable Manufacturing Systems (RMS)

2.1. Dedicated Manufacturing Lines (DML)

Manufacturing systems have evolved from job shops, which feature general purpose machines, low volume, high variety and significant human involvement, to high volume, low variety dedicated manufacturing lines (DMLs). These DMLs were developed in the automobile sector (mass production) where the manufacturing has an objective of high productivity. Earlier DMLs were based on mechanizing and then automation of the machining operations. Each dedicated line is typically dedicated to produce a particular part at a very high production rate. Each station of a DML is specialised to do an identical machining operation, always at the same place.

Henri Ford revolutionized the manufacturing system by introducing the principle of product flow through multiple stations. The DMLs have many advantages:

- very high productivity (Finel, 2004),
- high precision due to the fixation of the parts and the tools,
- low maintenance cost due to standardized equipment,
- high degree of automation, it improves the quality of the manufactured part (Belmkhtar, 2006),
- long life.

Since the 80’s, the DML became less attractive due to their inflexibility in the face of changing demand requirements and evolution of production in terms of product variety and production capacity. Thus DMLs are feasible only when we have fix demand in terms of variety and it corresponds to their capacity.

2.2. Flexible Manufacturing Systems (FMS)

In the 80s, Flexible Manufacturing Systems (FMS) were introduced. They address changes in work orders, production schedules, part-programs, and tooling for production of a part family. They can produce variety of products, with the changeable volume and part mix, on the same system. FMS is a technology that attempts to make the whole production system flexible and adaptable to changes in demand, without requiring any additional investment. The need to have a fast process flow and automation of complex tasks are the basis of their development. These systems can be modules of flexible manufacturing comprising of one or more computerized numerically controlled (CNC) machines or a single flexible manufacturing system (Figure 1). FMS were specially developed to respond to the constraints of productivity and flexibility.

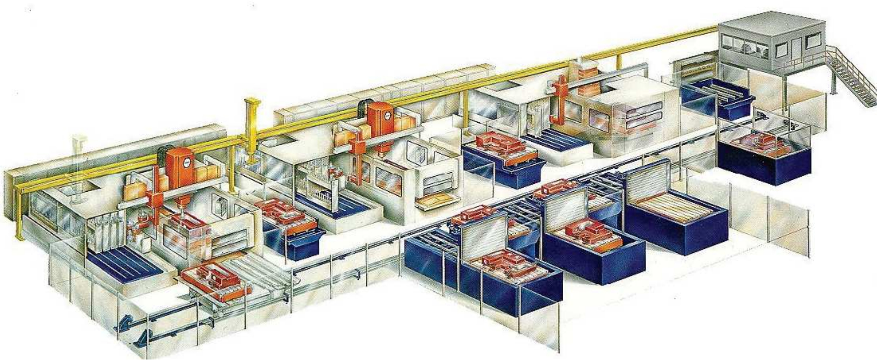

Figure 1 Example of a Flexible manufacturing layout having multiple machining cells

There are many factors which are contributing to the unsatisfactory performance of FMS. They include:

- high initial cost due to expensive general purpose computer numerically controlled (CNC) machines,
- complexity of the system,
- lack of reliability of software,
- need for highly skilled personnel and high support costs,
- inability to upgrade,
- production capacity lower than the desired level, (because of single tool operation, throughput less than that of DMLs).

According to (Mehrabi et al, 2002), the industries which have implemented and installed FMSs, more often the level of flexibility do not conform to the objectives. Almost two thirds of the industries do not use the complete functionality of these systems and there is a capital waste.

To cope with the short windows of opportunity for introduction of new products, computer aided design has dramatically reduced product development time during the last decade. However, such design methodologies do not exist for the manufacturing system itself, therefore the design time remains lengthy. Manufacturing system lead time has now become a bottleneck. These brief windows of opportunities can be captured, if lead-time of manufacturing system is reduced. This can be achieved through rapid design of systems that are created from modular components, or by the reconfiguration of the existing manufacturing systems to manufacture new products as depicted in Figure 2 (Koren et al, 1999). More recently, the reconfigurable manufacturing system (RMS) concept was introduced. It was done to respond to this new market oriented manufacturing environment.

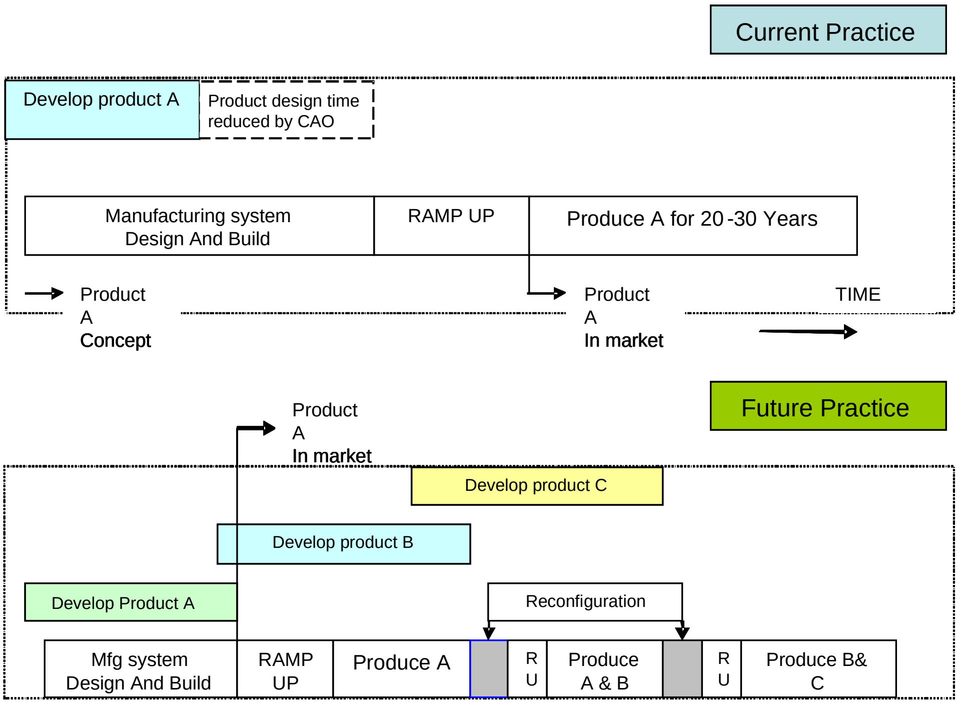

Figure 2 Comparison between current and future practices

A survey of literature suggests that there are several recent studies on various issues in future manufacturing and machine tools (survey by engineering research centre for reconfigurable machining Systems (ERC/RMS) (Koren, 1997), association for manufacturing technology (AMT) report 1996, national research council (NRC) report, 1998 and next generation manufacturing (NGM) report 1997), have identified some of the important drivers of the next generation manufacturing environment and also the attributes required to respond to these drivers are defined. The study carried out by National research council (NRC report) identified RMS concept as the number one priority technology for future manufacturing.

2.3. Reconfigurable Manufacturing Systems (RMS)

RMS are a cost effective response to market changes requires a new manufacturing approach that not only combines the high throughput of DML with the flexibility of FMS, but also is able to react to changes quickly and efficiently. Y. Koren has defined his article "Reconfigurable Manufacturing Systems" as:

"*The reconfigurable manufacturing system is designed at the outset for rapid changes in structure, as well as hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.*" *(Koren, 1997)*

The design of manufacturing system around part family, with the customized flexibility required for producing all parts of this part family. This reduces the system cost. RMS is designed to cope with situations where both productivity and the ability of the system to react to changes are very important.

2.4. Comparison between DML, FMS and RMS.

A comparison between the three systems globally based on the coordinates of capacity, functionality, flexibility, scope, cost… is carried out in Table 1. It shows that instead of providing a general flexibility through the complete life cycle of equipment with built-in high functionality as in FMS, RMS provides customized flexibility (Hu, 2006).

Factors	***DML***	***FMS***	***RMS***
• Complexity	Low	High	Medium
• System focus	Part	Machine	Part Family
• Skill level and training required	Low	High	Medium
• Capacity to integrate new additions	Low	Low	High
• Up gradation potential	Low	Low	High
• System structure	Rigid	Adjustable	Modular
• Machine structure	Rigid	Rigid	Adjustable
• Simultaneous operating Tools	Yes	No	Yes
• Production volume	Always High	Variable	Variable
• Product variety	Low	High- Very high	Medium- High
• System Ramp up Time	High	Medium	Medium
• Initial Cost	Low	High	Medium
• Flexibility	No	General	Customized
• Machine features	Dedicated and fixed feature	Versatile (CNC), variable no of axes, multi heads, multi spindle	Dedicated but changeable functions (axes, tools, etc)

Table 1 Comparison between DML, FMS and RMS

The objective of RMS is to combine a scalable output and an adjustable functionality with a minimum lead time and high productivity (Abele, 2006(b)). RMSs are designed to cope with situations where both productivity and the ability of the system to react to changes are of vital importance. An ideal RMS takes into account the the positives of both DMLs and FMSs (Koren, 2006). The architecture of RMS can be hierarchically structured as shown in Figure 3. On the system level Reconfigurable Machine Tools (RMT) are linked into sequential or parallel production lines (Abele, 2006(a)).

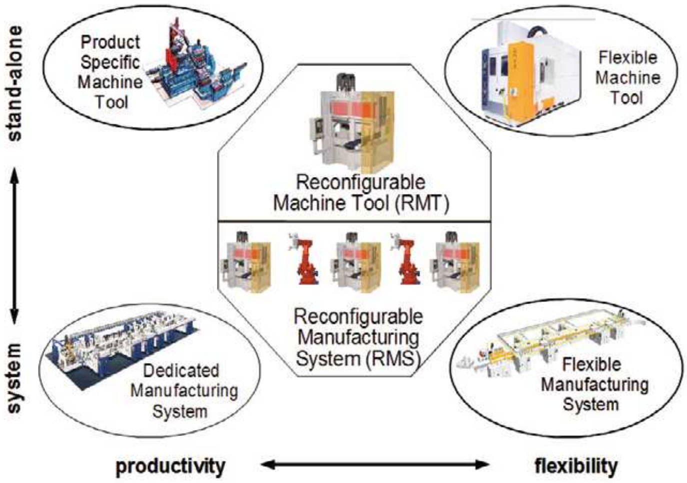

Figure 3 Classification of Manufacturing Systems (Abele, 2006(a))

2.5. Flexibility and reconfigurability

Elmaraghy in her article (H. Elmaraghy, 2006) describes the design, characteristics, and potential merits of RMSs and how they compare with other manufacturing paradigms at this stage of manufacturing systems evolution. Similarities and differences between RMS and FMS, the definitions of flexibility, reconfigurability, and changeability, and how to characterize a manufacturing system's responsiveness are discussed.

It states that an RMS is designed, at the outset, for a possible rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family while a FMS is a system whose machines are able to perform operations on a random sequence of parts of different types with little or no time or other expenditure for changeover. In practice, FMSs consist of processing stations and material handling systems that are entirely under computer control (CNC, DNC). In summary, RMS is a manufacturing system with customized flexibility and FMS is a manufacturing system with general flexibility (Hu, 2005). It is hypothesized that RMS is positioned between DML and FMS as shown in Figure 4.

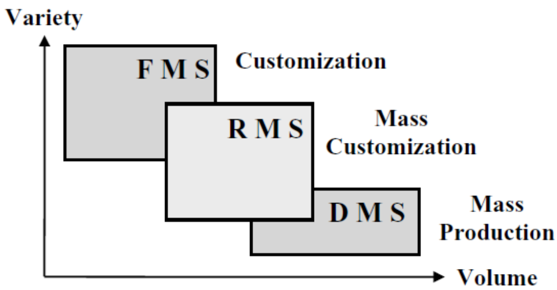

Figure 4 Manufacturing Paradigms—A hypothesis

3 Technologies enabling Reconfiguration

The common denominator for existing dedicated and flexible systems is their use of fixed hardware and fixed software. For example only part programs can be changed on CNC machines, but not the control algorithms. Therefore these systems, including CNC and FMS are static systems and are not reconfigurable. Two technologies that are necessary enablers for reconfiguration have emerged, software and hardware modularization. Reconfigurable hardware and software are necessary but not sufficient conditions for true RMS. The core of the RMS paradigm is an approach based on simultaneous design of open-architecture reconfigurable controllers with reconfigurable modular machines that can be designed by synthesis of motion modules. To fulfill the requirements of an open, modular machine structure, the modules and their interfaces must be carefully defined. When examining a self contained machine module, three main interfaces can be identified: mechanical, power and control or information. Only with the use of well defined interfaces, the reconfigurable manufacturing systems will become open-ended so they may be improved and upgraded rather than simply replaced. The survey by ERC/RMS deduced that the most important enabling technologies are: high speed machining (process), modular machine tools, open architecture systems, training of operators, and education of engineers. Enablers of manufacturing system transformability and classification of changeability were defined by (Wendahl, 2005) (Figure 5).

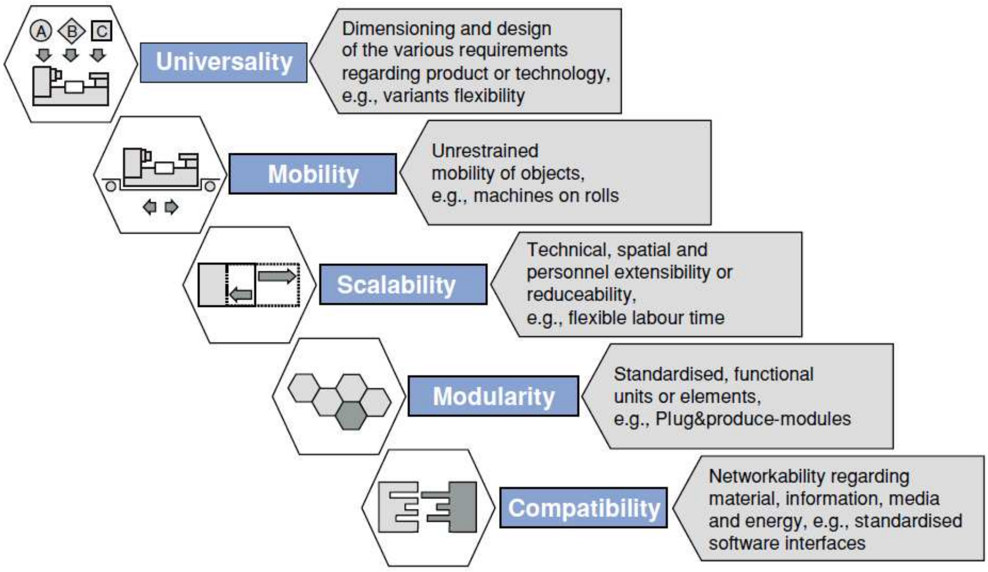

Figure 5 Enablers of manufacturing systems transformability

3.1. Key characteristics of RMS

A more precise classification the key characteristics of a RMS were done by Y. Koren (Koren et al, 1999). He defined in order to achieve the design goal requires several key characteristics, which are the following:

3.1.1 Modularity

In a reconfigurable manufacturing system all components are modular (e.g., structural elements, axes, controls, software, and tooling).

3.1.2 Integrability

Machine and control modules are designed with interfaces for component integration. The integrated system performance is predicted based on a given performance of its components and the interfaces of both software and machine hardware modules.

3.1.3 **Customization**

This characteristic has two aspects: customized flexibility and customized control. Customized flexibility means that the machines are built around the part family that is being manufactured and provide only the flexibility needed by it, thereby reducing costs. Customized control is achieved by integrating control modules with the help of open-architecture technology, providing the exact functions needed.

3.1.4 **Convertibility**

In the reconfigurable system the optimal operating mode is configured in batches that should be completed during one day, with short conversion time between the batches. Conversion requires changing tools, part-programs, and fixtures, and also may require manual adjustment of passive degree of freedom.

3.1.5 **Diagnosability**

Detecting unacceptable part quality is critical in reducing ramp-up time in RMS. As production systems are made more reconfigurable and are modified more frequently, it becomes essential to rapidly tune the newly reconfigured system so that it produces quality parts

Modularity, integrability, and diagonsability reduce the reconfiguration time and effort while customization and convertibility reduce cost. The system that possesses these characteristics has high level of reconfigurability.

3.2. Research Areas linked with the design of RMS

Advances in reconfigurable manufacturing will not occur without machine tools that have modular structures to provide the necessary characteristic for quick reconfiguration. However, the lack of machine tool design methodology and the lack of interfaces are the major barriers that impede modularity. Reconfiguration seems increasingly difficult for hardware interfaces, as they are much more difficult to realize that software interfaces. Following are the key research areas in RMS design:

3.2.1 **System Level Design issues in RMS**

A system configuration is defined as a set of machines (including controls) and connections among them.

3.2.2 **Life Cycle Economics**

If we take into account the entire life cycle cost of a production system in an uncertain market. Reconfigurable systems can be less expensive than FMS or DMLs. The main factor that makes RMS less expensive is that it is installed with precisely the production capacity and functionality needed and may be upgraded, in capacity and functionality, in the future, exactly when needed. It also eliminates the capital waste that occurs in FMS.

3.2.3 **Modular Structure**

Reconfigurable manufacturing systems need modular structure to meet the requirements of changeability, which is provided by a modular system structure. The primary goal of developing reconfigurable manufacturing systems is to develop machine modules, which can be quickly exchanged between different manufacturing systems. The exchangeability that can be accomplished by equal structure of the machines and the control systems and the standardization of the interfaces that combine the modules, which enables short term adaptability to market changes by reconfiguration of the system. The influence of the modular structure on the reconfigurability of the manufacturing systems depends on the choice of the module granularity.

3.2.4 Interfaces

To realize reconfigurable manufacturing systems and their modularity, standardization of the modules interfaces is required.

In this thesis, we concentrate on the technological aspects of a RMS related to machining operations. They are directly linked to the quality and cost of the feature that are required to be realized in a product family. RMTs are the basic building block of a RMS. They play a vital role in the transformation of the part family from its initial brut state to the finished state.

4 Design of Reconfigurable Machine Tool (RMT)

The concept of RMT enables the integration of multiple production functions in one machine workspace. The structure of RMT has a convertible design and consists of basic elements, which can be economically adapted through addition, substitution or structural change (Abele 2004).

RMT design should be based on two core methods i.e. design for modular reconfigurable machines and design principles for open structure architecture. In the existing approaches, the machine design methods should utilize a library of machine modules, each of which should be able to provide a fundamental motion.

4.1. Modular design

The modular design is the key enabling technology to reconfigurability, as the machining system can be easily reconfigured by simply adding, removing or changing the constituent modules or components. Modules feature a high degree of conversion flexibility, as again, they are composed of changeable sub modules (e.g.; spindle system or tools. Due to this flexibility a modification in the process plan to be executed, can be performed.

The primary aim of any reconfigurable machine tool is to cope with the following changes in products or parts to be manufactured:

- Work piece size
- Part geometry and complexity
- Production volume and production rate
- Required processes
- Accuracy requirements in terms of geometrical accuracy, surface quality, etc
- Material property, such as kind of material, hardness etc

To meet the productivity and quality demands of a machining operation, it must satisfy the variety of requirements including the ability to produce the specified motions and adhere to part tolerance specifications. Its kinematic viability and structural stiffness must be verified. Landers proposed a methodology to determine the kinematic requirements automatically (Landers, 2001).

In this method the machining operation is transformed into a task matrix that contains the necessary motion requirements of the machine tool. The functional requirements of the machining operation are used to generate a graph representation of candidate machine tools. This graph gives the overall topology of the machine tool. Modules are assigned to various portions of graphs. The product of their homogeneous transform matrix is compared to the task matrix. If equal then the machines are kinematically viable. The methodology is represented in Figure 6.

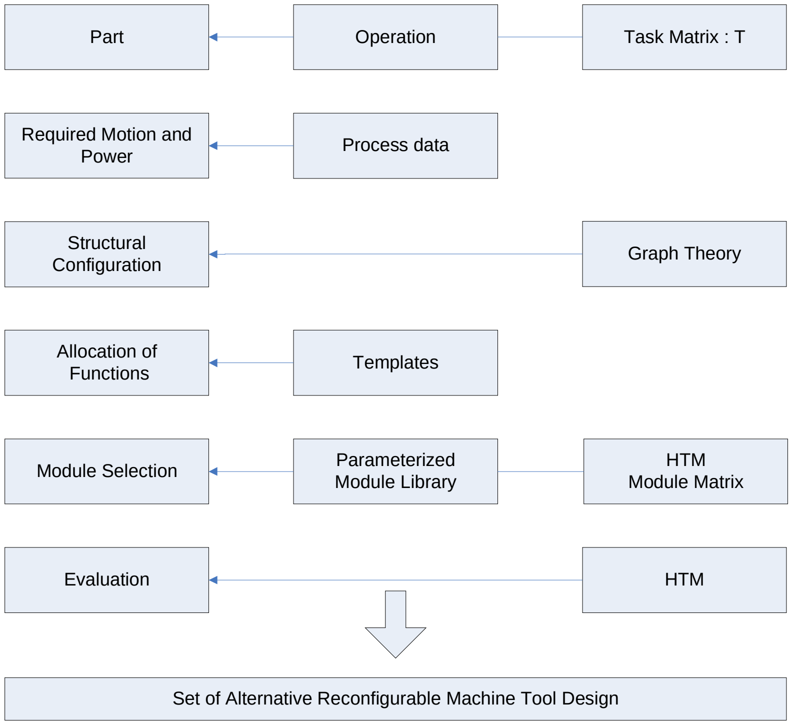

Figure 6 : Methodology for RMT Design (Landers, 2001)

4.2. Design of the Information and control

Similar to building a library of machine modules, controller software components are also stored and catalogued and stored for reuse. The modular design of machine tool equipment directly influences the requirements for the corresponding control equipment. To support the modularity, the control system must also be designed according to the principals of open architecture. By IEEE it is defined as "*An open system provides capability that enables properly implemented applications to run on a vide variety of platforms from multiple vendors, interoperate with other system applications and present a consistent style of interaction with the user*". In other words a neutral system platform which is independent of system applications and which can be easily adapted to specific hardware is indispensable to fulfil these requirements. The system software for an open control system defined as above has to contain at least three components.

- An operating system or run time module to execute the modules
- A configuration system to combine modules into a running system at boot up of the control.
- A communication system to enable information interchange between modules on the basis of standardized protocols.

4.3. Validation and system Ramp up of RMS

Ramp up time reduction is a critical objective for being able to respond to the short window of opportunity for new products as well as for scaling systems to cope with changing demand. The ramp up period is defined as "The period of time it takes to introduce a newly introduced or reconfigured manufacturing system to reach sustainable, long term levels of production in terms of through put and part quality, considering the impact of equipment and labor on productivity.

Achieving the objective of ramp up time reduction requires diagnostic and ramp up methodologies, at both system and machine level. As production systems are made more reconfigurable and their functionality and layouts are modified more frequently, it becomes essential to rapidly tune the system so that the opportunity is not lost.

5 Existing RMT designs

RMT is a piece of equipment that assures the transformation (especially through machining) in an autonomous manner while respecting the constraints of flexibility and productivity. Since the inception of RMS, numerous research works have been carried out regarding RMT design. A few important contributions in the domain of physical design of RMTs are listed below:

5.1. SHIVA, Multi-spindle machine tool

SHIVA is the first of the machine tools developed that touched the basic principles of RMTs and was developed by O. Garro and P. Martin (Garro, 1992; Garro and Martin, 1993). These works present a design methodology for the operational design of machine tools and it has implicitly integrated the concept of reconfigurability. Some years later, the methodology was further elaborated by Tollenaere (Tollenaere, 1998) using the concept of machining feature. The proposed method is oriented towards the design of physical elements of product manufacturing system.

The structural configuration of SHIVA consists of a large number of spindles which perform the machining operations on fixed work piece. The spindles work in either a sequential or simultaneous manner. For the machining features required to be realized, a search of functional architectural machining solutions of the machine tool is carried out. Garro proposed a mathematical formalization based on temporal logic.

Although, the method uses the concept of multiple spindles performing multiple operations at the same time, but it does not detail the steps required to take into account the positioning and maintaining the position of the work piece during the simultaneous operations (Aladad, 2009).

5.2. Arch-Type RMT

Professor Koren and his team at the ERC/RmS (Engineering Research Centre of Reconfigurable Machining System) developed the first real industrial RMT. This team essentially works for the automobile sector. The "Virtual Arch Type RMT" is designed at the outset for reconfiguration and the amount of reconfiguration is determined from the part family (Katz, 2000). We allow reconfiguring the machining angle in a discrete manner in the range of –15 up to 45 degrees.. However, the design took into consideration, a well defined "part family" with a well defined "family of functional features" such as some milling and drilling operations which take place on an inclined surface as shown in Figure 7. Drilling and milling operation on inclined surfaces are typical to many mechanical parts in the automotive industry and in many other industries. Therefore, it represents a wide span of realistic options to utilize the idea of angular reconfiguration and to apply this idea in a design of some other reconfigurable machine tools that will be built, to enable the change of the machining angle.

Figure 7 Example of a reconfigurable machine.

The RMT design methodology was developed by Y. Moon (Moon and Kota, 1999; Moon, 2000). The idea of Reconfigurable Machine Tool (RMT) goes beyond the concept of modularity in that a RMT allows mass customization, facilitates easy integration of new technologies. It is cost effective, and provides high-speed capability. The methodology presents a scientific basis for design of RMTs. An overview of the design approach is given in Figure 8.

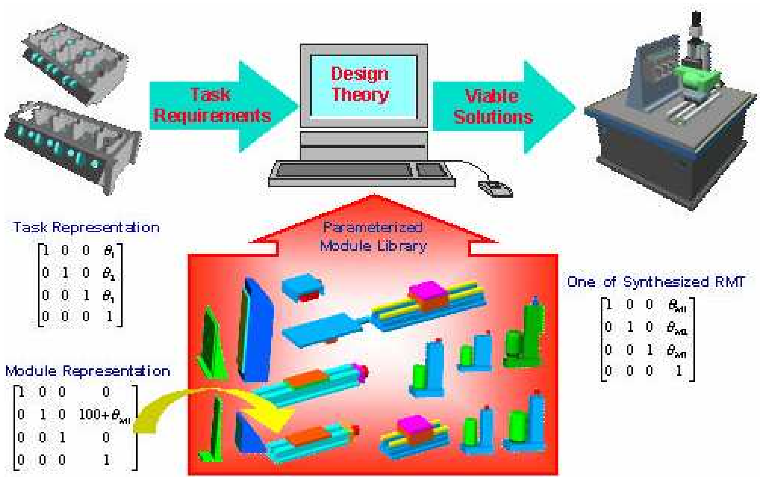

Figure 8 Overview of design methodology used for arch type RMT (Moon and Kota, 1999)

This approach requires the information regarding the process plans and module library before finding out the possible solution. Thus it is not completely independent of the processor structural domain. This is explained in detail in chapter 3.

5.3. METEOR 2010

The project "METEOR 2010" is a German research project aimed at standardizing the components of a RMT. The project consists of developing the principle of reconfigurability by modularity and adaptability of machine tools dedicated of machining. The modules of this machine tool should adhere to: minimum cost of transformability to new configurations, reduce break down time, capability to perform standard machining operations… This machine requires the standardization of all the interfaces.

5.4. Machine structure configuration approach

Shabaka and ElMaraghy in their work regarding generation of machine configurations based on product features (Shakaba, 2007), proposed a machine structure configuration approach. This approach is one of the recent additions in RMT design for a particular part. The inputs include part dimensions and tool directions for each operation required to be performed. The operation precedence graph is also an input. The approach requires clustering of machining operations and generation of machining operations. Figure 9, below gives an overview of the approach.

The output are the candidate machine tool configuration, machine modules, minimum axis of motion and angles of rotation required for each operation cluster. The approach uses the concept of mapping between the processing requirements of parts and the structural requirements of reconfigurable machine tool. It generates the minimum required machine capabilities for the machining cluster.

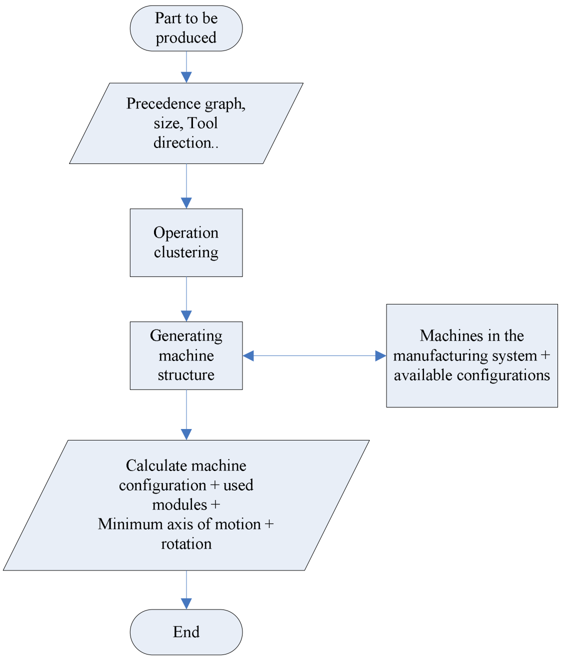

Figure 9 Machine structure configuration approach (Shabaka, 2007)

6 Summary

The new manufacturing paradigm of RMS is an important advancement in the field of manufacturing. It represents the market trends and possesses the capability to adapt to changes in requirement or market fluctuations. Major research societies including CIRP (Collège international pour la recherche en productique) and NSF (National science foundation of USA) are concentrating towards the development of these new systems.

Modularity is one of the most important characteristic of RMS concept, particularly with reference to RMT design and operation. The work of *Garro* is one of the first to introduce modularity in the manufacturing system. (Koren and Ulsoy, 2002) engaged in the development of RMS and RMT, with reference to industrial application. The solutions for the rapid changing or replacement of spindles and part holders are proposed by the PTW laboratory Darmstadt. It is responsible for the project METEOR 2010. One of the most significant contributions in the domain of RMT design came from Elmaraghy H.

The design of reconfigurable manufacturing systems is a complex process. It utilizes many different scientific domains. In context of the machining domain RMT plays a vital role. Its design includes the generation of structural configurations to realize the part family consisting of a group of manufacturing features. The literature review revealed that there is a need of a methodology that generates for a given set of functional requirements of the machining features, its corresponding process and structural domains. These domains need to be characterized by their machining processes and kinematic configurations.

Chapter 2

Formalization and Structuring of the framework of the Design Process of a Reconfigurable Manufacturing System

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Formalization and Structuring of the Framework of the Design Process of a Reconfigurable manufacturing system

This chapter focuses on formalizing the design process of a Reconfigurable Manufacturing System (RMS) and gives out a structured frame work to do so. A review of existing design approaches like axiomatic design and function-Behavior-Structure approaches was carried out. It was revealed that the existing works are oriented towards strategic design point of view. There is a need to have a methodology that links both strategic and operational design point of views, particularly with reference to Reconfigurable Manufacturing System design. They included non definition of physical solutions as design parameters and lack of formalism for the evaluation of the design solutions. In order to address these difficulties, the design approach is restructured with certain modifications. Performance domain is added in the design framework and performance indicators for each design parameter are defined. Evaluation is carried out by integrating "Function-Behavior-Structure" approach to the design methodology. An integrated design framework based on "Function-Behavior-Structure" approach and axiomatic design is presented. The knowledge base to support the transition process between the class variables of Function, Behavior and Structure is provided by manufacturing domain ontology called MASON.

1 Introduction

Manufacturing system can be defined as a combination of humans, machinery and equipment that are bound by a common material and information flow. A manufacturing system design can be conceptualized as a mapping from the performance requirements of a manufacturing system, onto suitable values of decision variables; which describe the physical design or the operating manner of a manufacturing system (Figure 10). Thus a manufacturing system design is viewed as a common, cyclical activity involving the definition of the system's objectives, the development of detailed system constraints and the implementation of the design.

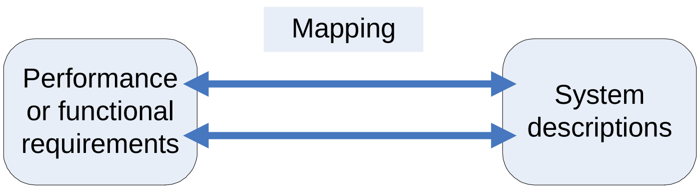


Figure 10 Manufacturing system design process (Chryssolouris, 1992)

There are number of product performance modeling, product design, and simulation tools for the manufacturing process. But the link between the manufacturing process and the design still needs to be formalized. This area has many important factors like enterprise, production resources, interaction between technical constraints and the size of the production line etc. The link consists of two aspects: the design of the manufacturing process and the design of manufacturing system. Use of a robust design methodology is necessary to handle the system design complexities involved in the design process. A framework to guide the designer through the decision making process while taking into account the effects of these decisions because of the interrelations between the sub domains is essential.

Design can be defined as "*interplay between what we want to achieve and how we want to achieve it*". Therefore a rigorous design approach must begin with an explicit statement of "what we want to achieve" and with a clear description of "how we will achieve it". The methods and tools for the design of manufacturing systems fall into three broad categories: operations research, artificial intelligence and simulation (Chryssolouris, 1992). There are numerous design approaches that are being followed by designers to undertake design of engineering problems. They include Theory of Inventive Problem Solving (TRIZ) (Altshuller, 1997), Axiomatic Design (AD) (Suh, 2001), Function-Behavior-Structure (FBS) (Gero, 1990) approach … These modeling and analysis methodologies have been developed to clarify the system design complexities.

Engineering design processes are fundamentally solution finding processes (Pahl and Beitz, 1996) that have to address the following aspects: specification of the requirements, search for solutions, evaluation of available solutions, and selection of the best suitable solution. Evaluation is in fact, evaluation of the design decisions. Our objective of the design of reconfigurable manufacturing system (RMS) leads us to some very important questions which will be answered in our proposed framework. They are:

- How to formalize and structure the design process for the design of a RMS?
- How to formalize the link between the functional needs and the physical elements of RMS?
- How to evaluate a design solution and define measurable performance indicators?

We have proposed a framework that assists reconfigurable manufacturing system designers in the structuring of the design process based on: functional requirements of the selected part family, structuring of knowledge required during the design process and defined evaluation criteria for reconfigurable manufacturing systems. The application of the function-behavior-structure paradigm made it possible to define functional characteristics at a level of abstraction that is suitable for their selection, configuration, and evaluation. Evaluation criteria were defined along with proposed methods of evaluation. Structuring and knowledge formalization with help of a manufacturing ontology MASON is illustrated.

Section 1 details different design approaches that include axiomatic design and Function-Behavior-Structure approach. Existing manufacturing system design frameworks based on axiomatic design methodology are detailed with respect to the design of RMS and the necessary additional parameters are highlighted. Driving design activities are detailed along with the transition of these functional activities into solutions. Existing work in the domain of manufacturing system design methodologies in general and reconfigurable system design approaches in particular revealed an emphasis towards the design at strategic level. Improvement of economic returns is one of the major objectives. On the other hand there are works (Bright et al, 2005; ElMaraghy et al, 2007) that focus on the operational aspect of manufacturing system design. But the connection between the strategic and operational level remains unexplored. We attempt to provide a link between the two levels.

In order to have a measurable performance parameters performance indicators are introduced in section 2. The design process from strategic point of view to an operational point of view is discussed. We propose the addition of the performance domain and performance indicators to carry out the evaluation of the generated solutions. A detailed framework for reconfigurable manufacturing system based on axiomatic design is presented.

To evaluate the solution and integrate the process domain for achieving a design based on functional requirements of a product family is carried out by adding FBS approach to the design framework. The application of FBS paradigm should make it possible to define characteristics at the level of their abstraction that is suitable for their selection, configuration and evaluation. Its integration with the proposed design based on axiomatic design theory is illustrated in section 3. This integration not only manages the transition from the functional to the structural domain but also permits the evaluation of the generated solution. Section 4 details the compatibility of a manufacturing ontology MASON and its role as supporting tool in the design process. The objective is to demonstrate MASON's capability to provide the necessary knowledge base during the design process.

2 Design Approaches

The design process may be defined as a hierarchical decision making process. Axiomatic design theory provides a valuable framework for guiding designers through the decision process to achieve positive results in terms of the final design object. The ability of AD in systematic propagation of functional requirements to the different facets of a system's design and the presence of existing axiomatic design based manufacturing system design frameworks, makes it a suitable approach.

2.1. Axiomatic Design

A methodology must be used to systematically relate the desired outcomes to design parameters that are used to achieve the desired results (Suh, 2001). Axiomatic design principles were introduced to establish a scientific basis for design and to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought process and tools (Kulak, 2005). Any design is made up of four domains: *customer* domain, *functional* domain, *physical* domain and *process* domain (Figure 11). The domain on the left relative to the domain on the right represents the goals / objectives while the domain on the right represents the design solution.

Customer's requirements are given in the form of Customer Attributes (CA). It is characterized by the needs (attributes) the customer is looking for in the final product / system. In the functional domain, the customer needs are specified in terms of functional requirements (FRs) and constraints to satisfy them. Subsequently, to satisfy the specified FRs, design parameters (DPs) in the physical domain are conceived. Lastly, to develop the DPs a process is developed that is characterized by process variables (PVs) in the process domain.

Axiomatic Design defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through mapping between Functional Requirements (FRs). These FRs represents "what we want to achieve" and Design Parameters (DPs) representing "how we choose to satisfy the need". The definition of these "what" and "how" is the base of axiomatic design methodology.

The customer needs (CNs) in the customer domain are mapped to the functional domain, where they are translated into a set of FRs. These FRs are minimum set of independent requirements that completely characterizes the functional needs of the product in the functional domain. By definition each FR is independent of every other FR at the time, FRs are established (Suh, 2001). Constraints will appear as a result of translation of customer wants to FRs and these constraints have to be respected through the whole design process. After defining the FR at the top level, a design concept has to be generated (Cochran, 1999).

The FR is then mapped to the physical domain and the DP is mapped to the process domain in terms of process variable (PV). The next step in this design process is the decomposition of the FRs, DPs and PVs in their sub sets. A decomposition hierarchy is formed by doing Zig-Zag (Figure 11) between the domains.

The process of zig-zagging between the functional and physical domains to lower levels provides a complete design decomposition of the strategic objectives (FRs) to the lowest level necessary to explain and determine the physical implementation. At the highest level the design FR is established with the available knowledge to complete the detailed design, the FRs and DPs decomposition i.e, leaf-level FRs and DPs. Throughout the decomposition process the designer is transforming the design intent expressed by the higher level design matrices into realizable detailed designs given by the lowest level design matrices. At each level of decomposition design decisions must be consistent with all higher level design decisions that were already made.

When the decomposition process propagates down to the lower levels, the design eventually reaches the leaf level, where one of more FRs can be fully satisfied (or controlled) by the selected set of DPs without further decomposition. The design process terminates when all of the lowest branches of the FR tree are leaves. A module is a row of design matrix that generates an FR when it is multiplied or supplied with a DP. Each FR leaf has one module that generates the FR given the input of DP.This mapping process is shown in the Figure 11.

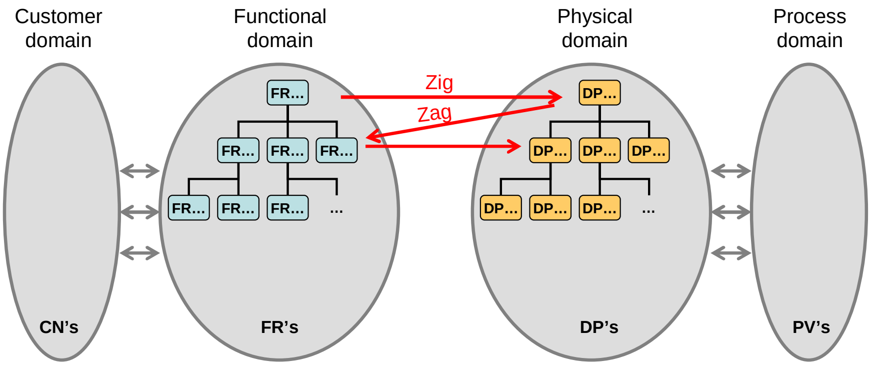


Figure 11 Axiomatic Design

The basic hypothesis of axiomatic design is that there are fundamental axioms that govern the design process. Nam Suh defines an axiom as self-evident or fundamental truth for which there are counterexamples or exceptions. In order for the mapping to be satisfied between two domains, two basic axioms must be followed:

- Axiom 1: The Independence Axiom – Maintain the independence of the functional requirements (FRs).
- Axiom 2: The Information Axiom – Minimize the information content of the design.

The independence axiom ensures that within a design, having two or more than two FRs, the FRs have to be defined in a way that satisfying one FR doesn't affect the fulfillment of the other FRs. The second axiom, the information axiom, is based on the idea that the success of a design is determined by the probability associated with achieving the FRs. This probability decreases with the amount of information necessary to fulfill the FRs.

The mapping process between the domains can be expressed mathematically in terms of the characteristic vectors that define the design. Goals and design solution at a given level of hierarchy, the set of FRs that define the specific design goals constitutes the FR vector in the functional domain. Similarly the set of design parameters in the physical domain that has been chosen to satisfy the FRs constitute the DP vectors. The relationship between these two vectors can be written as:

FR = [A] DP (1)

Where Aij is called the sensitivity matrix. It characterizes product design for a product having "i" FRs to be satisfied by "j" DPs. Depending on the form of the matrix Aij, the design can be classified as:

- ***Uncoupled Design.*** It is the most preferred design. It is a diagonal matrix indicating the independence of the FR-DP pair.
- ***Decoupled Design.*** It is the second choice. In this design the corresponding [A] matrix is triangular; therefore the FRs can be answered systematically. FR1 to FRn by only considering the first n DPs. This design appears most frequently in real life.
- ***Coupled Design.*** It is the undesirable type. In this design the |A| matrix has no special structure. Therefore a change in any DP may influence all FRs, simultaneously. In designing with AD-principles we try to avoid coupled design as much as possible.

2.2. Function-Behavior-Structure (FBS) Approach

FBS approach (function-behavior-structure) intends to improve the design of products or systems. It is directed to improve the design process. In FBS the act of designing can be seen as transforming a set of functional representations F to a design description or structure S through the behaviors B. Thus a designer develops a functional requirement F, determines behavior B, which will result in fulfillment of those functions and selects structures S to carry out the behaviors. The FBS framework represents the design development in different states. The basic assumption is the existence of three classes of variables required in a design process: function variables, behavior variables and structure variables. They are linked together by processes, which transform one class into another.

Gero (Gero, 1990) has introduced a representation schema for design knowledge, i.e. knowledge about existing (physical) or to be designed (imaginary) objects, based on the notions of function (F), behaviour (B) and structure (S). The three major components of the approach are:

- Function (F) describes the teleology of an object.
- Behavior (B) describes the attributes that are derived or expected to be derived from the structure (S) of an object.
- Structure (S) describes the components of an object and their relationships.

Michel Labrousse in his thesis (Labrousse 2004) carried out a literature survey of various definitions of function, behavior and structures. After careful comparison and discussion, he proposed more generic definitions of each class variables. The functions describe in an abstract manner the objectives of the object (product, process or resource). They are formulated independently of any particular solution or choice of structure. Behavior may include a set of laws and rules (continuous models) and a series of sequential states (discrete models) representing the evolution of a structure following an excitation during a given process. While, a structure allows to specify the elements that make up the object model and the attributes of these elements.

Hu (Hu et al, 2000) defined Function, Behavior and Structure (FBS) model as an approach for designing devices which explicitly represents the functions of the device (the problem) , the structure of the device (the solution), and the internal causal behaviors of the device. Function can be defined as what (an object) does, behavior as how (it) does what (it) does, and structure as what (an object) is.

Application of FBS involves representing a particular product /system by its required functions. Connections between function, behavior and structure are constructed. Specifically, functions are ascribed to behavior and derive behavior from structure. A direct connection between function and structure, however, is not established.

It is an approach which represents in an explicit manner, the functions of the product or of the system (the problem), the structure of the product (Solution) and the behavior (process) internal to the product. The objects are considered as three views (functional, behavioral and structural) and are supposed to be able to be defined while passing successively from one view to other. In FBS the design process is divided into eight different steps by which the designer transforms the functions F into design descriptions as shown in Figure 12:

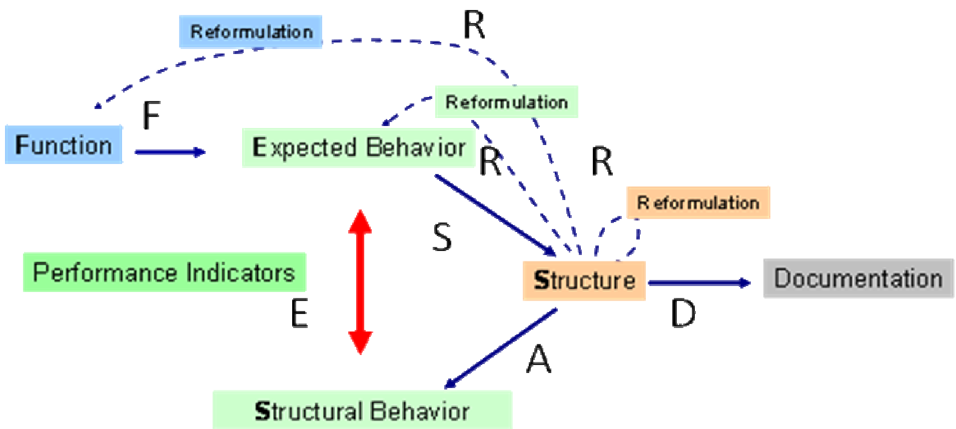


Figure 12 Function - Behavior - Structure Approach

- **F**ormulation: Transforms the design requirements, expressed in function (F), into behavior (Be) that is expected to enable this function.
- **S**ynthesis: Transforms the expected behavior (Be) into a solution structure (S) that is intended to exhibit this desired behavior.
- **A**nalysis: Derives the "actual" behavior (Bs) from the synthesized structure (S).
- **E**valuation: Compares the behavior derived from structure (Bs) with the expected behavior (Be) to prepare the decision if the design solution is to be accepted.
- **D**ocumentation: Produces the design description (D) for constructing or manufacturing the product.
- **R**eformulation: Addresses changes in the design (S).
- **R**eformulation: Addresses changes in expected behavior (Be).
- **R**eformulation: Addresses changes in the functions (F).

2.3. Axiomatic Design of Manufacturing Systems – Analysis and Modifications

Designing a manufacturing system to have a set of strategic objectives involves making a series of complex decisions over time. Making these decisions in a way that supports the organization's high level objectives require an understanding of how detailed design issues affect the interactions among various components of a manufacturing system. In practice, designing the details of manufacturing systems (equipment design and specification, layout, manual and automatic work content, material and informational flow, etc) in a way that is supportive of a firm's business strategy has proven a difficult challenge. Since manufacturing systems are complex entities involving many interacting elements, it can be difficult to understand the impact of detailed, low-level deficiencies and change the performance of a manufacturing system as a whole.

For the design of manufacturing systems the decomposition in the functional and Physical domain (design solutions to achieve the Functional Requirements (FRs)) is most effective (Suh, 2001; Cochran and Reynal, 1996). To achieve the desired goals of a manufacturing enterprise, manufacturing systems must be designed to satisfy a specific set of functional requirements based on the customer requirements and manufacturing constraints (Garro and Martin, 1993). Recent works includes feature based axiomatic design method of Li Chen's (Chen, 2005) for optimal module selection for reconfigurable machine tools (RMS) and Manufacturing System Design Decomposition (MSDD) approach (Figure 13).

2.3.1 Optimal module selection methodology

Module selection method is directed towards generation of preliminary design solutions of reconfigurable machine tool (RMT), but its solution space is confined by the provided FR-DP database. Axiomatic Design principles are used to introduce a feature-based method for selecting an optimal set of modules required to construct a reconfigurable machine tool capable of producing a particular part family.

The technique of grouping together parts of similar shapes, dimensions, producing technologies and functions as a family of work pieces was used in "Group Technology concept" (Halevi, 1995; Ham, 1985). Group Technology can be summed up as the identification and exploitation of geometrical and technological similarity of characteristics and attributes of a product for higher productivity by the formation of part families (han, 1994). In the context of RMS, a part family is defined as all parts (or products) that have similar geometric features and shapes, the same level of tolerances, require the same processes, and are within the same range of cost. The definition of the part family must ensure that most manufacturing system resources are utilized for the production of every member part.

By optimal it is meant that the size of the selected set is minimum, yet sufficient in forming a reconfigurable machine tool which is able to machine a family of parts. Here the geometric features that signify a set of unique machinable features of a part are referred as FRs, while the machine modules that signify structural constituent units of machine tool as DPs.

A few basic concepts are defined below; these are to be used in the explanation of methodology for module selection (Chen, 2005).

- Configuration. It is a specific layout of the machine tool dedicated to machining a specific part from a family. Different arrangements of the machine modules will correspond to different layouts, or rather, different configurations of the machine tool. In order to machine a given part, the reconfigurable machine tool must adopt a certain configuration that is dedicated by the machine module used and their arrangement.
- Local Module. It is defined as the module with respect to a specific configuration. A module is said to be local if it is discussed in the context of a single configuration.

- Global Module. It is a module with respect to all required configurations. A module is said to be global if it is discussed in the context of all the configurations together.
- Axiom 1. Maintain the both the functional and physical autonomy of local modules.(Important when selecting the local modules)
- Axiom2. Maximize the number of common global modules. (Important when extracting common global modules across different configurations

The module selection method effects module selection and we begin by considering machine tools at high level, and then move to a lower level through decomposition of those machine tools into their constituent units. Later, selection formalism is developed to computerize the module selection procedure.

In the method, successful design of reconfigurable machine tool rests on the premise of a proper set of available machine modules. Also machining process plan is an input to the design methodology. Thus the reconfiguration is possible at structural level only. The essential presence of a module library limits the scope. However it does provide an axiomatic design framework.

2.3.2 Manufacturing System Design Decomposition (MSDD)

MSDD (Cochran and Linck, 2001), shows how an enterprise can simultaneously achieve objectives such as cost, quality, delivery responsiveness to the customer and flexibility. The need for MSDD was felt because the previous work only described the objectives in their concerned hierarchy and it did not clearly distinguish between objectives and means to achieve them.

The Axiomatic design principles are used in the MSDD approach. In case of MSDD, decomposition proceeds for as long as it is possible to do so without limiting the usefulness or range of applicability of the decomposition. According to axiomatic design principles, when further decomposition of a DP is needed, FRs for the next level are determined. The goal of this decomposition is to decompose the high level FR-DP pairs into their low level components. In Figure 13, reading from left to right, the MSDD shows path dependence. The FR-DP pair on each level are arranged in such a way that the pair whose DP influences the most FRs is on the left side. We see that quality, problem resolution, predictable output, throughput time reduction and labor reduction are critical factors in implementing the desired system design goals. Hence decisions should also be made following MSDD from left to right.

The decomposition process defines the foremost requirement of any manufacturing system as “maximize long-term return on investment (ROI)” It is labeled as FR1. In this context, long-term return on investment ROI refers to the lifecycle of a given system. ROI is taken as the highest-level focus of the manufacturing function as it represents a general objective that is applicable to a wide variety of manufacturing environments and is not inherently contradictory to any accepted improvement activities. To satisfy the above mentioned FR1, its corresponding DP1 is defined as “manufacturing system design”. Basing on the factors affecting ROI, this DP1 is further decomposed to generate new functional requirements (FRs) of maximizing sales revenue, minimize production costs and minimizing investment over the production life cycle. Accordingly, the DPs are selected to satisfy the newly defined functional requirements. The overall objective of MSDD is economic and maximizing the profits. All activities are directed to achieve this goal.

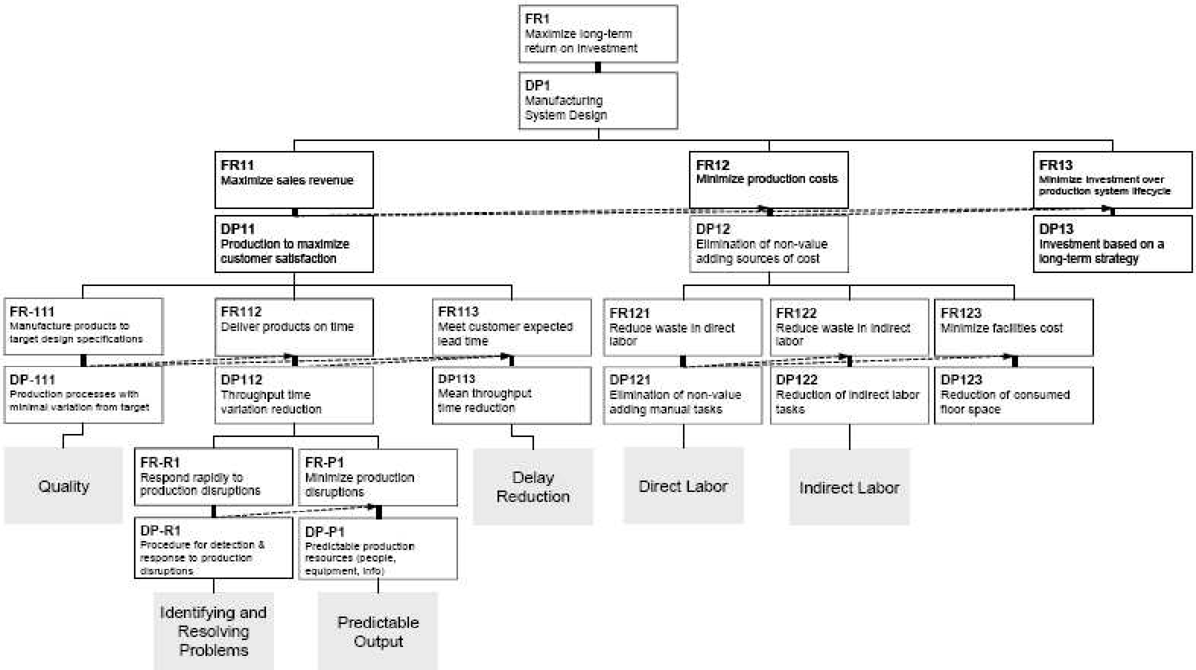


Figure 13 Levels of MSDD showing its different domains (Cochran and Linck, 2001)

Study of MSDD with respect to manufacturing system design highlights that FRs are independent of the specific physical entities such as manufacturing stations or cells. The goal of MSDD is to structure the stated FRs and to achieve independence through the selection of design parameters DPs. The process of decomposition relates low-level design decisions to high level system objectives, and shows design sequence by highlighting which decisions are required to be taken first. MSDD highlights the critical relationships between a FR and the physical or logical solution (DP); therefore it is considered as a decision support tool (Cochran and Reinhart, 2000).

However MSDD does not guide us to a complete specification of the physical entity. Professor Cochran and his team at MIT advanced MSDD to propose a framework called Product Delivery System (PDS) (Hendricks, 2002, Cochran and Rudolf, 2003, Cochran 2003).

2.3.3 Product Delivery System (PDS)

The PDS approach, during the decomposition process focuses on the domains of product design, quality, cost and delay reduction. This approach goes a step further in designing of the manufacturing system. It moves beyond the static definition of the FR-DP relationship. PDS applies the axiomatic design in the allocation of constrained resources to achieve system design requirements. It represents the design for a stable manufacturing system that operates with the fewest resources. PDS gives the system design in its entirety. The requirements for system stability are defined, which gives the attributes for a successful manufacturing system. It is a path dependent design and clearly illustrates the importance of dependencies in manufacturing system design. The path dependent decomposition in the PDS is shown below in the Figure 14.

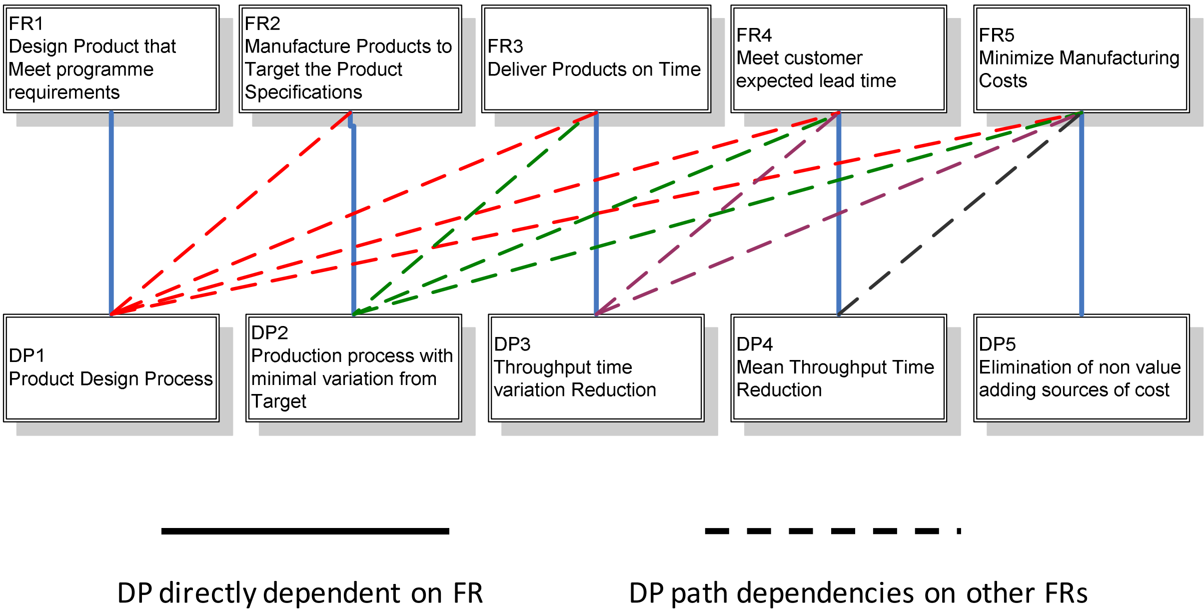


Figure 14 High Level Path dependent Design of the PDS

However, we noted that both the above mentioned approaches are interlinked and their objective is to provide a framework that gives the design processes i.e. the activities that are required to be performed during the design process. The FRs are functions of the design processes for a manufacturing system while the DPs are the activities for the design processes. However they are not the physical entities (Figure 15). In the MSDD/PDS the DPs have a measurable performance (MP) associated to it, e.g. Delays: throughput time reduction. Each design activity results in some measureable performance. This measured performance effects the complete satisfaction of FR. As in the stated example The FR is "To meet customer expected lead time" and its design activity was defined by Cochran as "Delay reduction. In this case time is the measureable performance parameter.

On the other hand application of axiomatic design methodology for RMS design results in a set of FRs which must be satisfied with the help of corresponding DPs. These DPs or design solutions can be described as an arrangement of reconfigurable physical entities of machine tools.

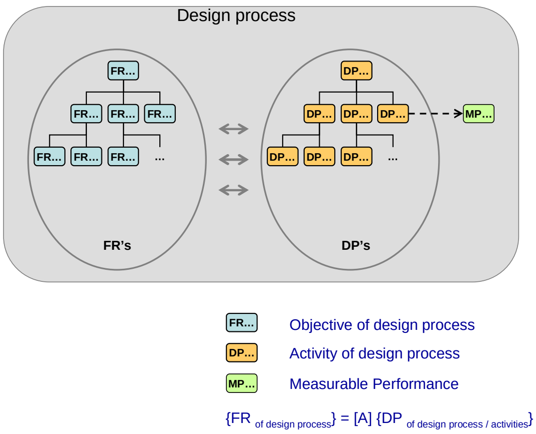


Figure 15 Axiomatic design applied to the design process of a manufacturing system

MSDD/PDS design decomposition process is very efficient to define the link between the strategic level and activities of the design process. For the approach MSDD and PDS the strategic level is characterized by “return on investment (ROI)”, which is an economic indicator. To be globally competitive, many large industrial firms are attempting to adopt "lean" manufacturing. The axiomatic design approach has been deployed for the design of manufacturing system in the lean manufacturing framework

In short the manufacturing system design methodologies proposed by Cochran provides us:

- An economic objective oriented methodology. E.g. “FR1= Improve ROI”.
- Clearly stated FRs.
- DPs in terms of activities of the of the design process.
- Each activity of the design process is primarily dependent on the FR it satisfies. Thus there is dependence between the objectives and the activities. Path dependency shows that it is impossible to effectively achieve FR12 when FRl 1 (Figure 14) has not been satisfied; a design has not been implemented until all of the FR-DP pairs illustrated, are achieved.
- The activities of the design process “DPs” do not provide the physical solutions when applied in case RMS design.

In short the link between the strategic and the physical level cannot be clearly illustrated by the above mentioned applications. MSDD / PDS propose the design activities as design parameters and not the physical elements.

3 Design framework for a reconfigurable manufacturing system using axiomatic design and function-behavior-structure approach and integration of performance domain

In order to formalize the relations between the objectives of evolution emitting from the strategy of concurrent engineering and the uncertainty in market trends, improving ROI alone is not sufficient. It is necessary to add other robustness criteria. The laboratory “Production system design” (PSD) of M.IT, applied axiomatic design to construct a functional model. This model is between the functional need derived from the lean manufacturing concept and the means to satisfy these needs. MSDD distinguish the strategic level from the functional needs and the means to satisfy them and the physical level which represents the model of the system under study. However the model developed by MSDD/ PDS is incomplete. In fact this model does not propose a link between the strategic level and the physical or operational level; it proposes the interface between the functional needs of the design process and the activities of the design process of the physical manufacturing system. It is very important to note that in this approach, the DPs are the activities that define the physical system, but not the design solution themselves.

We have observed some deficiencies in applying the axiomatic approach for the design of a RMS: the link between the strategic level (very much developed in lean manufacturing) and the physical solutions, and the concept of performance measurement.

- Firstly, we are interested in the construction of the relations between the functional needs of RMS and the physical elements of RMS. The FRs are decomposed and classified in terms of product family range, capabilities (quality, geometric characteristics, precision…), time and cost. Thus a FR is a function of RMS and a DP is defined as an element of RMS. An example of this can be that for FR5 in Figure 14, “Minimize manufacturing Costs”, the corresponding DP is defined as: “Elimination of non value adding sources of cost". Therefore in PDS, a DP is an activity directed towards realizing the objective of design.

- Secondly, the concept of performance measurement is not included i.e. it is not clear whether the defined DP has completely satisfied the selected FR or not. To overcome this deficiency, we propose a new domain of performance indicators (PI) to be integrated in the design approach. They are evaluated from the DPs of RMS. The definition of performance indicators is rendered necessary not only to evaluate the solutions between themselves or with respect to the expected performance to make a choice but also to evaluate the pertinence of a design activity.

The objective of this design process is to provide a solution in terms of a manufacturing system. We attempt to complement the existing work of MSDD and PDS by providing a complete design framework.

As discussed earlier the existing manufacturing system design approaches provide solutions in terms of activities of the design process The objective of this frame work is the construction of the relations between the functional needs for the RMS and the physical elements of the RMS i.e. the link between the activities of the design process as defined in MSDD and the physical level characterized by entities of RMS. Axiomatic design to RMS must satisfy a set of FRs and it can be described as an arrangement of reconfigurable physical entities of machine tools (Figure 16).

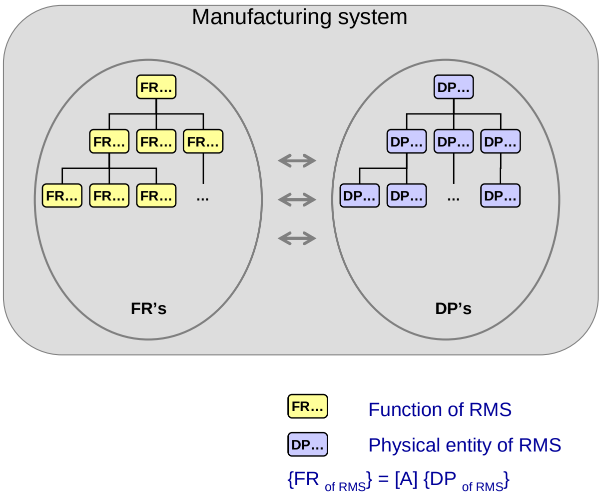


Figure 16 Axiomatic design applied to Reconfigurable Manufacturing System design

The application of AD principles for RMS design should result in a set of DPs which are physical entities of RMS but the concept of associated measurable performance (MP), initially available in PDS, will be missing. Therefore, we propose to add Function-Behavior-Structure approach and complement the design process adopted by MSDD by including the concept of the Performance Indicators (PIs). The concept of PI with respect to the FRs of the RMS is explained in the section 3. They are defined in relation to the DPs (design activities in MSDD) of the design process. To allow the evaluation of the design through the selected PIs, we have proposed to integrate FBS design approach.

3.1. Design process

The proposed design in this research work is based on AD principles like PDS. The basic parameters like capability to produce the chosen product family, quality of the produced product, production delays and cost are chosen as essential domains for the manufacturing system. As per AD principles the FRs are to be derived from the customer attributes and DPs be defined to satisfy/realize the FRs. The proposed design of a RMS which complements and derives from MSDD, but instead of the activities or physical solution as DPs (discussed earlier), we have used the concept of performance indicators. The deployment of axiomatic design for the design of a physical manufacturing system of RMS is proposed as shown above in Figure 16 and a supplementary performance domain which allows to link between the design activities and physical solutions. The integration of performance domain in the design process will be explained in detail in the subsequent section.

The application of axiomatic design for the design of RMS architecture, the transition of FRs to DP is done directly and no particular manufacturing processes required during the transition of the FRs to RMS solution. For example, in the axiomatic design framework for the design of RMS/RMT, one of the FRs is 'The manufacturing system should be capable to manufacture all the products in the product family", the corresponding DP is 'the manufacturing system architecture". The passage of the RMS functions to its architecture requires the definition of the processes which are necessary to accomplish them. This deficiency is removed by adding the FBS approach to the design framework.

3.2. Integration of FBS approach for the design of RMS

As discussed earlier, in all the manufacturing system design approaches transition from FRs to DPs is done directly. The particular manufacturing processes necessary for the transition of FRs to the solutions DPs for RMS are not defined. Also the concept of the evaluation of the design solution is not catered for. In fact, the transformation of the functions of the RMS to its architecture requires the definition of standard processes of manufacturing, it thus seems relevant, to utilize the approach Function-Behavior-Structure (FBS) (Gero 1990). The objects are considered according to three different views i.e. functional, behavioral and structural, and are supposed to be able to be defined while passing successively from one view to another. The addition of this approach with respect to Axiomatic Design, within the framework of the design of a RMS, enables us to integrate the manufacturing processes via the behavior portion of FBS.

The concept of performance indicators (PIs) have been integrated in the approach. It utilizes the concept of performance measurement of the expected or desired performance with respect to the real performance of the solution proposed by the approach. The utilization of the approach requires as how to represent and model the three principle elements of FBS(Figure 17): the function, behavior and structure for the design of a RMS / RMT? (Baqai and Dantan, 2007).

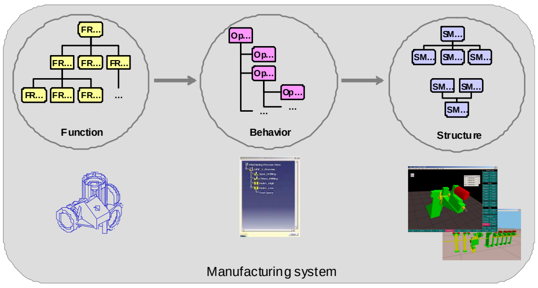


Figure 17 Deployment of FBS approach to RMS design

3.2.1 Functions

For the design of machine tool the functions are the purposes or the expected capabilities. These functions are based on the requirements of the product family. The important question that arises is how to characterize and describe a product family? In case of manufacturing system design functions are defined as

"Functions are the geometric and dimensional needs based on the part family. They include all part specifications like geometrical and dimensional specifications"

The common methods to represent a product family are: to characterize with respect to all the entities in the product family required to be realized. This can be done by decomposing a manufacturing part into its constituent manufacturing features i.e. representation by entities or by grouping of parts / manufacturing features having similar characteristics i.e. by group technology. A part is a set of manufacturing entities / features. According to the French community GAMA, a machining feature is a semantic set characterized by a collection of parameters used to describe an indecomposable object relative to one or more activities related on the design and the use of products and systems of production (Tollenare 1998). Thus a manufacturing entity or feature should not only be represented by geometric definition but also with its associated manufacturing process. Here is where the behavior aspect comes into play.

3.2.2 Behavior

A designer constructs connections between the function, behavior and structure of a design object through experience. Specifically, the designer ascribes function to behavior and derives behavior from structure. A direct connection between function and structure, however, is not established. The behavior for a machine tool design represents dynamics of an object. They are the processes that the machine tool must be able to do. This will depend on the machining operations required to completely realize the product family for which the machine tool is being designed. Thus the behavior part can be characterized by:

"System behavior is characterized by listing all the required machine operations, their precedence relationships, required degrees of freedom and the probable directions of machining".

Moreover in FBS approach, it is possible to integrate a distinction between the expected and the structural (actual) behavior. The expected behavior Be is derived from the functions. It is primarily the translation of the specifications of the functional requirements. The Structural or actual behavior Bs is derived from the structure and thus entirely depend on the choices of solution. The goal of a design process is to make Be and Bs coincide as much as possible and to adjust them if necessary. In the case of a manufacturing process, the behavior is that of the machine tools, or is its result, i.e. the characteristics of the product manufactured (cost, quality, times).

3.2.3 Structure

Lastly the *structure* represents the interpretation of the functions in the form of a proposed design.

"Structure is represented by a set of proposed solutions i.e. by a set of probable architectural configurations of a RMS".

In the scope this work, we have limited to the study of the mechanical aspect of the kinematic structural configurations. The control and logistic aspect has not been considered. These configurations would be analyzed for the given constraints (time, cost, quality, structural characteristics….) and the most suitable will be selected. The evaluation of the solutions is done by using performance indicators. The implemented performance indicators should be representative of the various concepts characterizing the performance.

However, in case of the design of RMS, this comparison becomes very subjective i.e. comparing the desired and actual machining processes. Comparing real and expected machining operations becomes very difficult. The desired functionality can be more related to the out put of the system i.e. functionality that emits from the structure. Also the aim of RMS design requires an evaluation at the resulting solution. In fact, the functions are relative to the products that a RMS must produce, so a more tangible and qualitative comparison can be done between the expected and achieved functions with the help of performance indicator i.e. between the products that are expected to be produced and those that are actually produced Figure 18. Therefore the comparison and evaluation is proposed to be carried out at the functional level.

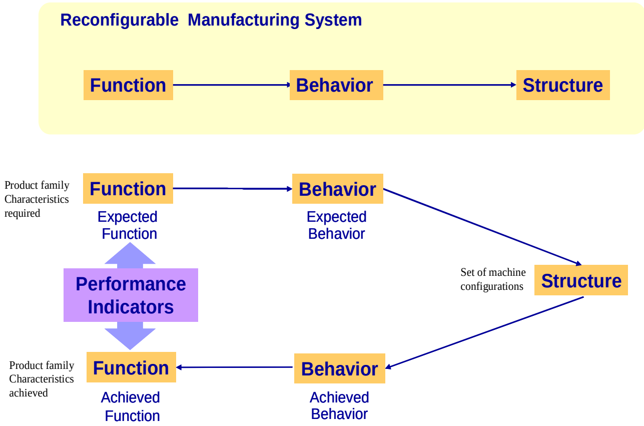


Figure 18 Application of FBS for design of RMS

3.3. Design Steps

The application of the FBS approach for the design of RMS is proposed to be done in two phases. The first phase consists of generation / design / synthesis of the solutions: definition of the functions with respect to the requirements and the transitions from the functional domain to the behavioral and finally to structural domain. We need to define certain rules to govern this transition. E.g. rules/criteria for the choice of machining operations to create the manufacturing features and the grouping of operations based on the given constraints. The second phase consists of analysis, evaluation and selection of the solutions.

The first phase is of generation/design/synthesis of solutions: the definition of the functions with respect to the needs and the transition from the functional to behavioral domain and subsequently from the behavioral to structural domain. To achieve this we need to define a set of rules to govern these transitions i.e. criteria for selection of manufacturing processes to realize the manufacturing features and rules for grouping several operations basing on the given constraints. These rules can be defined as constraints or be taken from machining visiting card of each entity. The concept of “machining visiting card” or “carte de visite” (Villeneuve 1993) will be explained in the subsequent chapter. Possible solution approaches include modeling of the problem as a constraint satisfaction problem or using algorithmic techniques to explore the whole solution space.

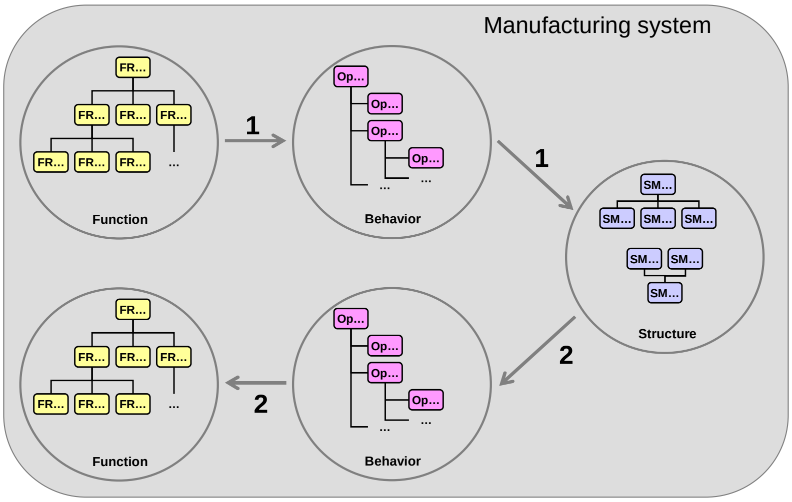


Figure 19 Design Steps

3.4. Integration of performance domain

Initially, we restricted our performance evaluation to measuring the efficacy, which results from the comparison between the real or achieved functions (who are representative of the results) and the expected functions (which result from the objectives). Briefly Performance Indicators (PIs) are financial and non-financial metrics used to quantify objectives to reflect the strategic performance of an organization. They help define and measure progress towards organizational goals. A PI is a variable indicating the effectiveness and / or efficiency of a part or whole of the process or system against a given norm / target or plans (Fortuin, 1988).

We propose to do the design decomposition of the FRs and their corresponding Performance Indicators (PIs). The advantage of using PIs is that they are not directly associated with the design activities and therefore not restricted to any particular activity. However they are directly linked with the FRs of the RMS like DPs. is shown in Figure 20. These performance indicators make a connection between the MSDD/ PDS approach and our work.

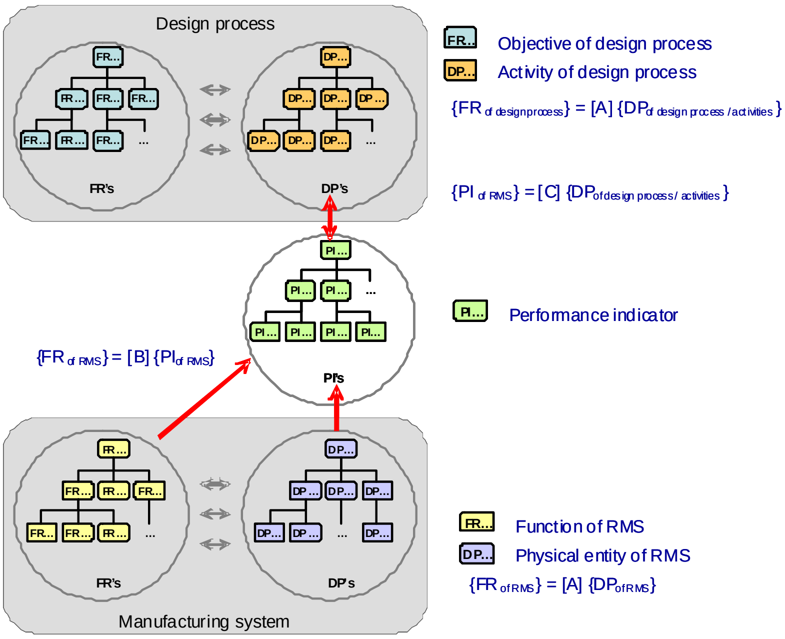


Figure 20 Design Framework of RMS

The construction of the design matrix is done in similar fashion as described in AD theory and done in MSDD and PDS:

$$\{FR_{\text{of RMS}}\} = [B]\ \{PI_{\text{of RMS}}\}$$

We have carried out the definition of the FRs and their corresponding PIs as DPs along with the path dependencies. The corresponding design activities are defined in MSDD /PDS already discussed. The relationship between the two can also be represented like the FR-DP design equation of AD and can be written as:

$$\{\text{PI of RMS}\} = [C]\ \{\text{DP of design process / activities}\}$$

The relationship between the RMS design as design activities and RMS design with the supplementary concept of PIs is illustrated in Figure 20.

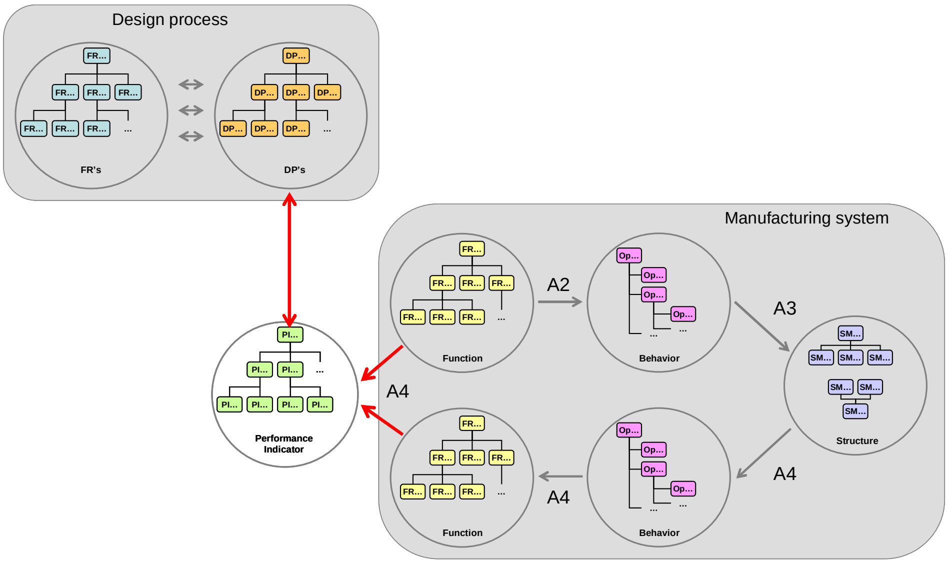


Figure 21 PI as a link between frameworks based on axiomatic design and FBS approach

The definition of the performance indicators is rendered necessary due to the requirement of evaluating the solutions with respect to the expected performance, to carry out the choice. Thus the PI forms a link between MSDD/PDS and the FBS approach for the design of RMT/RMS as shown in Figure 21.

3.5. Decomposition of PI's

Based on AD principles, a framework showing the performance domain in terms of defined PIs for the given FRs was developed. Its decomposition up to level 3 is shown in Figure 22. For each functional requirement its corresponding DP (design activity) and PI are then selected. In our objective of RMS design, the first step in the design based on AD principles is the definition of the functional requirements (FR) at the highest level which reflects the enterprise long term objectives.

With the current market scenario, it is essential to have a manufacturing system that is capable to achieve the production goals and it is not just limited to manufacturing of a single product. From the highly sophisticated and costly built-in functionality, the requirement has changed to have minimum built-in functionality that is capable of upgrading at a later stage (Mehrabi and Koren, 2002; Kulak, 2005). It should have the characteristics of volume flexibility, desired product quality, ability to transport the work-piece / product (Koren and Lenders, 2001), quick detection of variance from desired level of performance and the system to be quickly ramped-up and validated after reconfiguration. Group of part features belonging to a par family and their corresponding machining operations are related to machine modules, so as to enable product-process integration. At system level, the machines are a group of machining modules that are integrated via material transport systems (such as conveyors and gantries) to form a reconfigurable system.

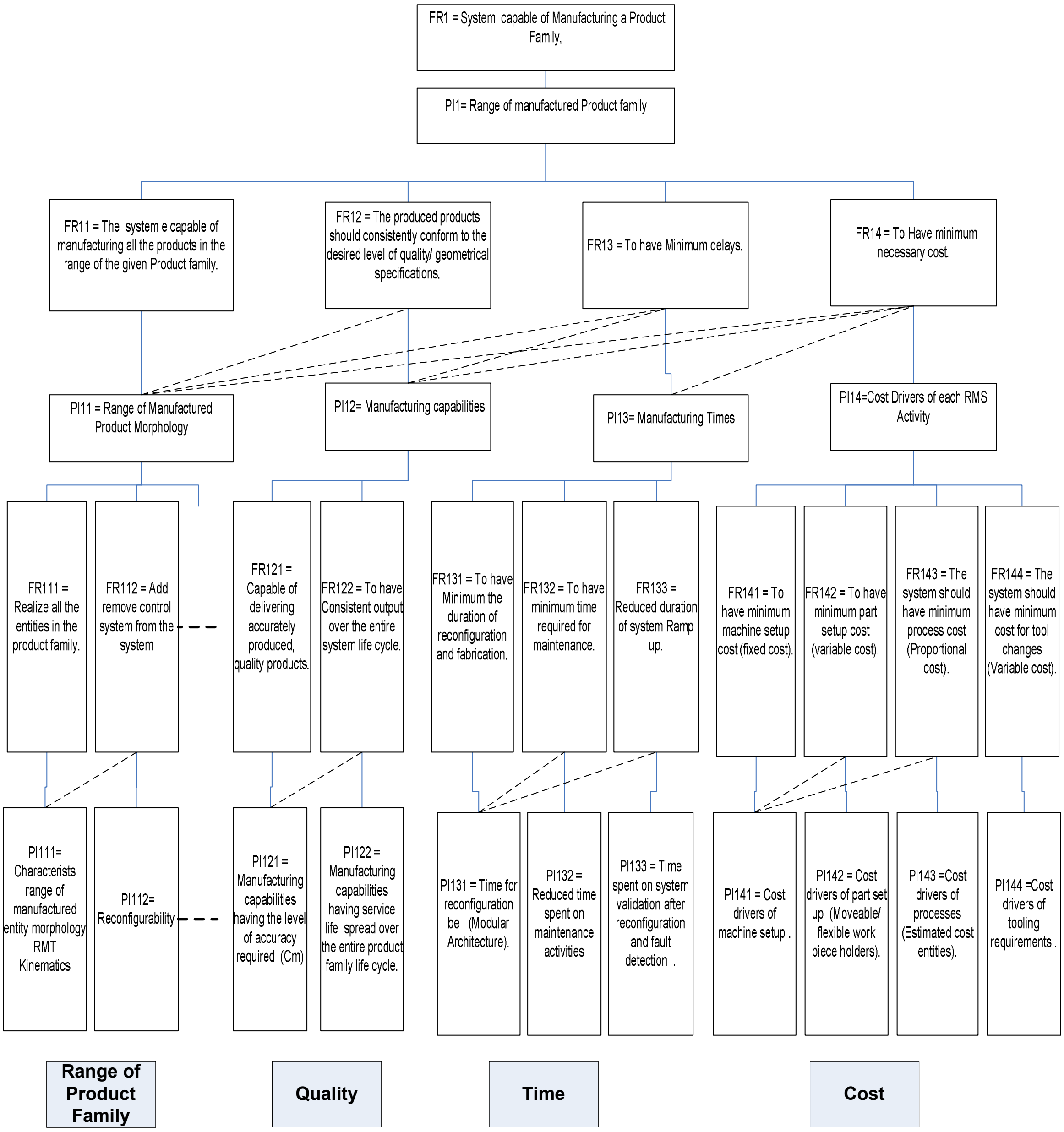


Figure 22 FR-PI Decomposition

Keeping in view the above mentioned requirements, the functional requirement at the highest level can be stated as:

FR1 = System to be capable of Manufacturing a Product Family, for the given constraints.

The design parameter, which satisfies the FRs established, is selected through a mapping process between functional domain and physical domain. The following DP has been selected to satisfy the FR provided above.

DP1 = Reconfigurable Manufacturing System.

This design parameter is developed in detail in chapter 3, where different design solutions are explained in detail. The design solutions are based on structural configurations of the RMS. These configurations include spindle / tool change modules and part rotation fixtures. The solutions are spanned from all machining operations on a single post to spread over multiple posts. At this level of decomposition, we have limited ourselves to the functionality and design concerning with technological aspects. The control system and transport system are not taken into account. However, in this chapter we intend to formalize the design process of RMS which is independent of the choice of configuration i.e. DPs. Thus it is essential to find a link between the axiomatic design based on design activities and the one having physical elements. The performance indicators ‘PIs’ provide the necessary link.

Evaluation of the design solutions for production systems is not a new concept. Olivier Garro in his thesis (Garro(a) 1992) discussed in detail the evaluation of design solutions and criterions for evaluation for production system design. He explained that initial design is evaluated by the designer on the major criterions of productivity, flexibility and cost. Other criterions include reliability, ergonomic design, security and maintainability. But these other criterions are evaluated when the structural choice has been made. Flexibility according to Garro can be measured on two complementary axes i.e. time or hierarchal decomposition. It can be part change flexibility, design change flexibility or volume flexibility. According to Pourcel (Pourcel, 1986), productivity is an interaction between a certain quantity of product and one or many production factors. Finally cost is the cost of production including all cost incurring activities.

With reference to the design of RMS, we will focus on effectiveness of the design solution. The following PI has been selected to satisfy the FR provided above.

PI1 = Characteristics Range of manufactured product family.

I.e. the production system is based on part family which can integrate the product design changes while maintaining the desired quality and adhering to the cost and time constraints.

To explain and clarify the PI selected, AD principles recommended returning to the functional domain for decomposing the 1st FR into its lower functional requirement set. The proposed design framework defines that a RMS should have the capability to produce the whole range of products for which it is designed (Garro and Martin, 1993). The produced products should have consistent quality as demanded by the customer or decided by the higher management. The cost of the produced product should be as low as possible. Cochran also emphasized the importance of the delivery time in the production and manufacturing process. Also there is an associated cost of reconfiguration. Work has already been carried out on a methodology to measure the ease of reconfigurability called “smoothness” (Ayman and Hoda A. ElMaraghy, 2006). Further to make a design selection based on required time for reconfiguration an approach has been proposed by (Galan et al, 2007). According to PDS, the manufacturing system should be such that the production delays should either be eliminated or at least reduced to the very minimum. Using the AD principles and assisted by the PDS, following FR-PI set is defined. As discussed before the FR-PI pair at the top level is

FR1 = System to be capable of Manufacturing a Product Family, for the given constraints.

PI1 = Complete range of manufactured product family.

I.e. the production system is based on part family which can integrate the product design changes while maintaining the desired quality, time and adhering to the cost constraints. The fore mentioned characteristics of product family, quality, time and cost are taken as the core concepts and second level functional requirements. Their corresponding PIs are selected. They include: RMS architecture, manufacturing capabilities, manufacturing time and cost driver of each RMS activity. An example of one of the decomposed FR-PI pair is product family realization. FR11 concerning with Product family is further decomposed so as to explain all the aspects related to system based on product family. In general the functional domain of a system designed to produce a particular product family must have certain necessary functional characteristics. It should have the capability to manufacture all the products in the family range and be able to carry out all the movements required to produce the products i.e. have necessary degrees of freedom and possess the process capability required to manufacture the designated product family (Kota 2002) It should have common basic control and informational structure with the ability to add / remove product specific additional components (Koren, 1999 and Koren, 1993).

FR11 = System to be capable of manufacturing all the products in the range of given product family.

PI11 = Range of manufactured product morphology.

This is further decomposed to 2nd level FR-PI which deals with the realization of all the entities in the product range. The concerning DP for the FR is capability of having all the kinematics in the designed RMS for the particular Product family (Cochran, 1996). Unlike CNC machines, RMS are tailored to give the initial operational requirements for realizing the entities rather than the beforehand inbuilt functionality that leads to capital waste (Kulkak, 2005). Therefore for each product in the product range the functionality has to be increased or decreased. It is designed to process a given family of machining feature. It is designed to process a given family of machining features from a set of standard modules. The operation plan considered as basis for design of RMS, consists of a family of machining features including machine operation types, cutter locations and process plans (Bohez 2001):

FR111 = Realize all the entities in the product family product range.

PI111 = Characteristic range of manufactured entity morphology – RMT kinematics

In the decomposition, we have limited ourselves to the functionality and design concerning with technological aspects. The control system and transport system are not taken into account. The technological aspects or RMS and process and machine accuracy are concerned with.

Figure 23 shows the tree structure of the evaluation framework. The defined evaluation criterions of product family range, quality, time and cost are interlinked with path dependencies. In order to globally evaluate the design solution there is a need to have common indicator. For this the methods for aggregation of performance indicators like ECOGRAI and SPEC can be applied. The proposition for aggregation of performance indicators has been explained by M. Samuel Schmidt as his “Projet fin d’études (PFE)” (Samuel, 2008) at ENSAM Paris Tech.

The above illustrated framework is derived from the axiomatic design principles based MSDD and PDS. Since the design activities have been replaced by physical entities, the measurable performance parameter needs to be addressed. The application of axiomatic design methodology for the design of manufacturing systems in general and RMS in particular, the transition from FRs to DPs is done directly. The particular fabrication processes during the transition from FRs to the RMS solutions are not defined. E.g. in axiomatic design framework for the design of a manufacturing system, the FR at the top level is “The system should be able to manufacture all the parts in the product family”. Its corresponding DP is defined as “RMS architecture”. The transition from functional requirement of RMS to its architecture requires the processes that are necessary to accomplish it. This problem is resolved by the integration of FBS approach. This design approach allows taking into account the manufacturing processes as system behavior.

The knowledge base to support the transition process and between the class variables of Function, Behavior and Structure can be provided by manufacturing domain ontology called MASON. In our work we have demonstrated the compatibility of MASON developed at ENSAM with our RMS design methodology.

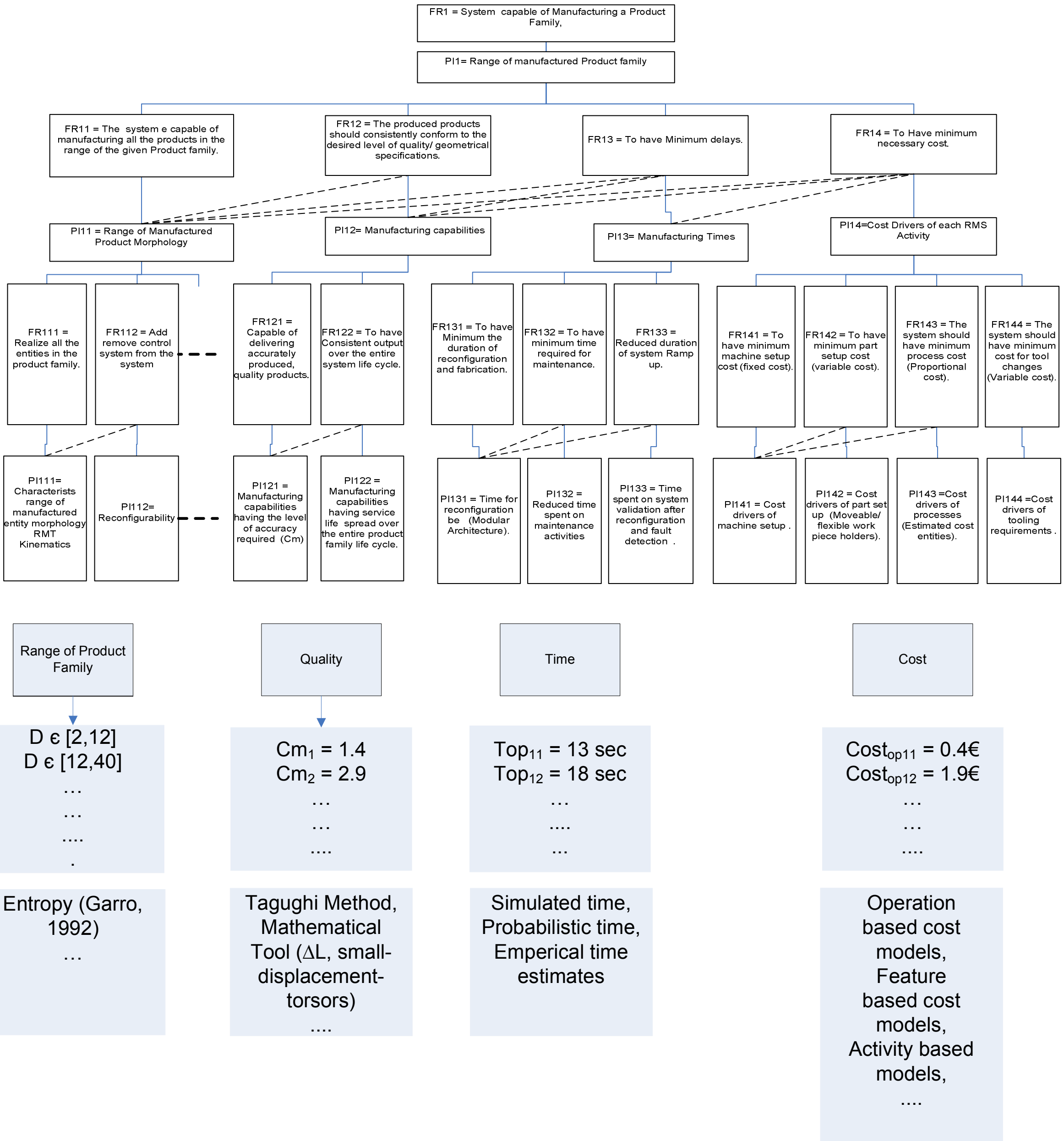


Figure 23 Need for aggregation of the performance indicators

3.6. Formalization of the design Framework

The RMS design methodology based on the application of FBS approach, requires the two transitions i.e. from the functional to the behavioral domain and from the behavioral to the structural domain. Therefore the successful application of the design approach depends on how these transitions are managed. The whole design process based on FBS approach can be divided in five main activities.

- *Definition of expected functions A1*: Product design specifications along with customer requirements are taken as inputs and formal part model is generated. This model serves as an input to the subsequent activity. In our case of RMS design part data specifications are formalized in the form of part model.
- *Generation of machining operations and precedence relationships A2*: This activity generates the pre-process plans having different combinations of machining sequences for a part to be machined. Also for each of the pre-process plan, corresponding precedence relationships between different machining features with respect to machining are generated in the form of a matrix.
- *Generation of process plans and structural configurations A3*: The complete solution space is explored and all possible process plans along with their corresponding kinematic configurations will be generated in this activity.
- *Evaluation A4*: The generated preliminary designs design solutions are evaluated with different methods/tools according to already defined criterions with their corresponding performance indicators.
- *Selection A5:* After aggregation of different performance indicators selection of optimal design solution is carried out.

The design process can be represented with help of an activity diagram (Figure 24).

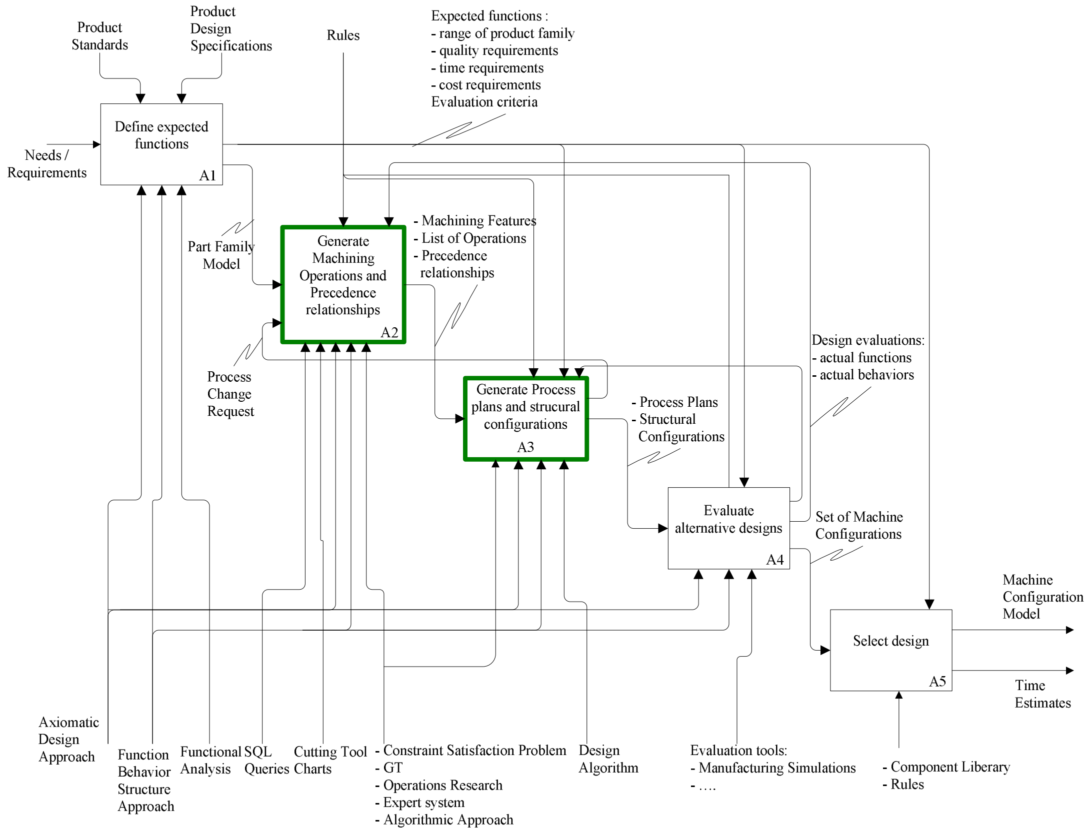


Figure 24 IDEF0 Activity diagram of the design Process of Reconfigurable Manufacturing System

4 Design framework and manufacturing ontology MASON

Next generation manufacturing companies have to become highly responsive in order to succeed in an ever more rapidly changing global market. The ability to effectively develop and adapt their facilities (systems) to changing requirements on demand plays a crucial role in achieving high responsiveness since the assembly process has to deal with the full inherent complexity of increasingly mass-customized products.

This work on knowledge formalization in the manufacturing domain was motivated by the current lack of a holistic manufacturing system design theory that would enable design environments to address the need for rapid system development and adaptation. The challenge is to create a common environment where domain experts can effectively collaborate while taking advantage of the best practices of their diverse domains. This section investigates how domain ontology can help to overcome those challenges. The approach is taking advantage of the higher levels of standardization inherent in the modular manufacturing system paradigm which is considered to be one of the fundamental enabling factors to achieve a high level of adaptation. Integrated and knowledge enabled methodologies are one way to reduce the design and integration effort by making the right information available at the right time and by providing state-of-the-art engineering tools that support the development.

Information systems have nowadays well-known and well mastered architectures. However rules, and shared corpus of definition, lack a widely recognized formalism. Ontologies are semantic tools that address that kind of issue. Ontology is concerned with the study of being or existence and their basic categories and relationships, to determine what entities or what type entities exist. They help to clarify a domain knowledge structure and therefore improve knowledge sharing, utilization of captured knowledge and maintenance of existing knowledge (Chandrasekaran et al, 1999; Grunninger and Lee, 2002). In information science, ontology is a data model that represents a set of concepts within a domain and the relationships between those concepts. It is used to reason about the objects within that domain. They are a formalized description of concepts and relationships (both taxonomic and semantic) that exist between these concepts.

A lot of work has been carried out on the tools and methods of representation of data and knowledge, directed towards artificial intelligence to solve problems involved in the computer-integrated manufacturing and the industrial engineering. The concept of ontology providing a knowledge base has already been incorporated in various applications using different tools, e.g. for cost estimation using expert system, for production optimization and simulation using multi agents.

The implication for supporting design frameworks and knowledge ontologies is that they should provide mechanisms that take advantage of this higher level of standardization. This opens the scope and need for higher degree of integration and automation during the design of such systems. Development of an ontology framework for the integrated design of modular assembly systems has been proposed by Niels LOHSE (Lohse(a), 2006, Lohse(b), 2006). He proposed a new ontology framework has been developed to support the design and adaptation of modular assembly systems (ONTOMAS). The ONTOMAS framework is based on engineering ontology principles structuring the domain using formalisms for aggregation, topology, taxonomies, and system theory principles. A number of design patterns have been identified and formalized to support key design decision-making tasks during the design of modular assembly systems. Furthermore, the function-behavior-structure paradigm has been applied to capture the characteristics of modular assembly equipment at different levels of abstraction that reflect the specific needs of the engineering design process.

The aim of this work is to define a suitable design framework and supporting ontologies that enable rapid design of modular assembly systems. The objectives include the definition of a suitable design framework, the definition of the required domain concepts and their interrelationships, as well as the definition of suitable knowledge support formalisms to guide and support the design process.

MAnufacturing's Semantics Ontology (MASON) was developed at in LGIPM at ENSAM in Protégé (Lemaignan, 2006). It is an ontology definition and instantiation framework that provides a software environment for the definition of ontologies. The ontology can be instantiated and made available as a knowledge base for both internal and external utilization. In our work MASON act as a support to the design activity. It provides semantic relations between the concepts and also the constraints. However it does not provide operational relations. After demonstrating the compatibility of MASON with our framework, any further work will have clearly defined semantic relations o follow. A brief overview of the manufacturing ontology and the compatibility of the key concepts of entity (product) – operation (process) and resource is shown in the following sub sections.

4.1. MASON

Manufacturing domain has been described by Patrick Martin (Martin 2003) as the sum of product, process and resource concepts. Thus, dealing with a manufacturing system means dealing with these concepts. i.e., having control over them, as well as on the bindings occurring between them. These bindings are driven by three main elements: an information System, rules and a common dictionary.

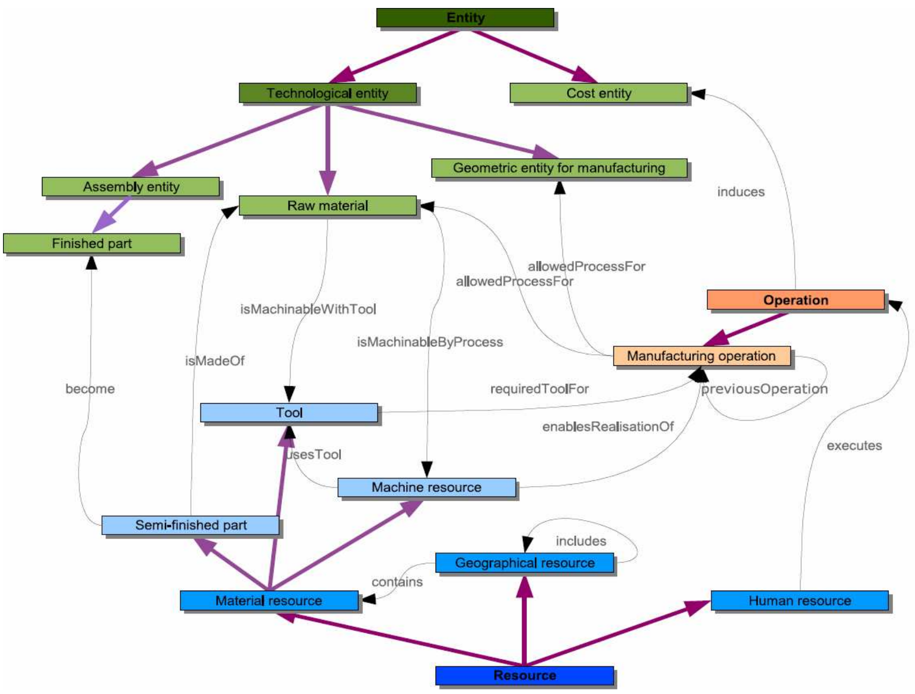


Figure 25 Overview of the ontology's main classes and object properties

As shown in Figure 25, the ontology is built upon three head concepts: entities, operations and resources. The transition process is governed by certain rules which are represented by the taxonomic relationships. A correspondence may be roughly established with Martin's decomposition of manufacturing in product, process and resource. Figure 25 shows main sub concepts which inherit from head concepts as well as main relationships between these concepts. The figure is a small subset of the whole ontology which contains today up to 270 base concepts and 50 properties binding them.

4.1.1 Entities

Entities are all the common helper concepts. They aim to provide concepts to specify the product. It gives an abstract view on the product. The most important sub concepts amongst these entities are:

- Geometric entities and Geometric entities for manufacturing which represent respectively abstract (like isTangentTo) and concrete (like Chamfer) geometric features,
- Raw material, actually viewed as abstract features of parts,
- Cost entities which represent basic cost features as defined by H'Mida (H'Mida 2006).

An example of axial boring entity is given in Figure 26. The concept of entity / machining feature will be explained in detail in chapter 3.

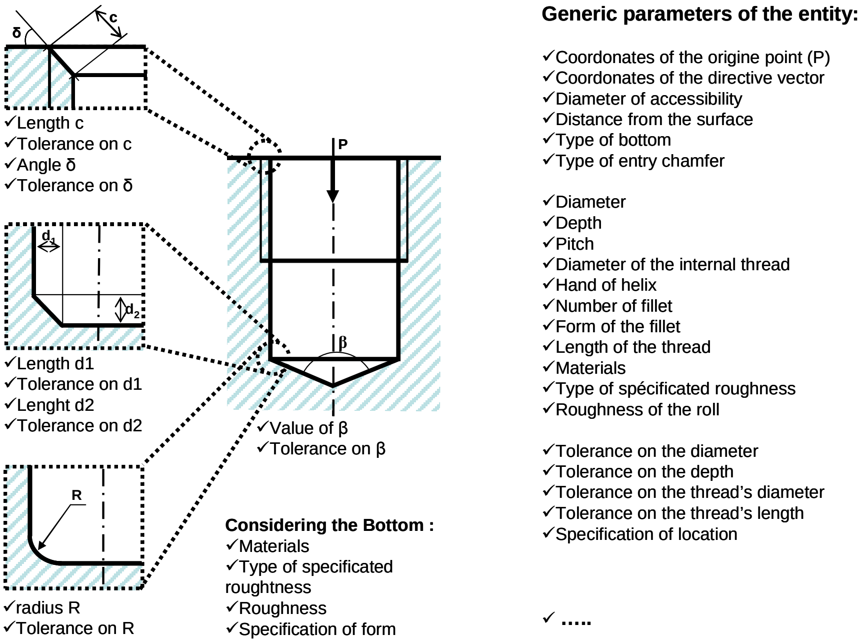


Figure 26 The MEGF "Non-through tapped bore" and its parameters (Etienne 2006)

4.1.2 Operations

Operations relate to process description. They cover all processes linked to manufacturing in a wide acceptation:

- Manufacturing operations, including machining operation as well as control or assembly. Machining operations are further classified according to their physical features (slow/brutal; hot/warm; with/without loss of volume...).
- Logistic operations,
- Human operations,
- Launching operation,
- Transportation,
- Setup,

-
-
-

4.1.3 Resources

Finally resources stand for the whole set of manufacturing linked resource, like:

- Machine-tools,
    - Axe,
    - Motor,
    - Bed,
    - Slide,
    - .
    - .
    - .
- Tools,
- Human resources,
- Geographic resources (like plants, workshops...),
-
-
-

The above mentioned three concepts form the base of the ontology MASON. Their application with respect to the design of manufacturing systems is explained in the following sections.

4.2. Correspondence

As the design of machine tool is divided into its three sub domains i.e. Function, Behavior and structure, the important question arises "*how to represent and manage the process of transition between the domains?*" It is here the ontology MASON comes in effect. It provides the knowledge base and the semantic relations between key domains and their sun concepts.. Similar use of ontology for a manufacturing process (forging) to store and exploit knowledge has been carried out by P. Martin (Martin, 2007).

The ontology MASON has been subdivided into three major classes i.e. entity, operation and resource. A function in FBS approach can be correlated with the entity in MASON, as the functions are based on the product requirements which are actually the entities / manufacturing features that are required to be manufactured. The desired or actual behavior from a manufacturing system can be represented as the type of operations it can perform. Finally the structure in FBS approach for manufacturing system design can be represented as the resource generated or created to perform the required behavior i.e. operations or machine capabilities.

The taxonomic relations give the rules that govern the relationships / transition between the domains. Therefore the transition from one domain to the other is subject to the rules already specified under the ontology.

In MASON taxonomic relationship between the operation and entity concepts represent the information contained in the cutting tool chart. It associates the manufacturing operations with the geometric description. This is represented in the relation below and illustrated in Figure 27.

Taxonomic Relation in MASON = Machining Process Information

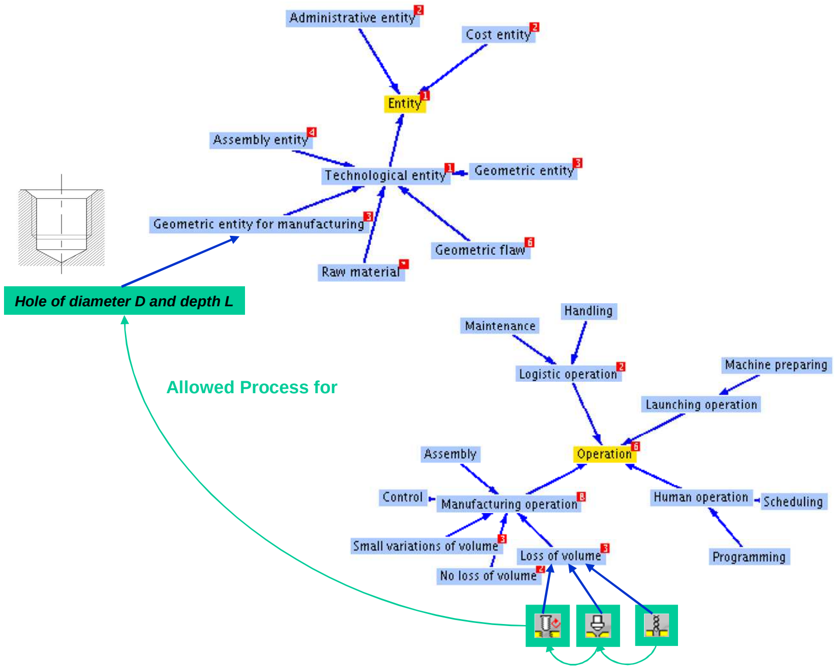


Figure 27 Association of manufacturing processes to an instance of the entity concept

We have shown with this simple example that each taxonomic and semantic relationship represents a particular practical application.

5 Conclusion

The design of a RMS requires the precise statement of the design objectives in terms of functional requirements and measurable solutions in terms of design parameters. In view of the system design complexities, a robust frame to guide the designer through decision process is essential. The problem statement includes two very important questions i.e. how to formalize and structure the design process for the design of a RMS? and how to identify and evaluate the performance of the RMS design process?

The traditional approaches towards manufacturing system design are no more applicable on the new system paradigms as the criterions for the development on process plans and structural configurations have been modified. This requires a new approach that integrates specific development requirements. Our proposed framework attempts to provide the link between the strategic and operational levels. Design formalism is provided which adapts the FBS approach and integrates AD principles for the design of RMS.

In this chapter we have focused in developing design framework of RMS and in particular:

a) Performance domain is developed and integrated in Axiomatic design process of RMS. This overcomes the problem of measurable design parameters. Performance indicators are defined to measure and evaluate the defined design parameters, performance indicators have been introduced as a performance measuring parameter. These performance indicators act as the constraints for selection. Furthermore these selected constraints serve as objective function for the optimization of the design process for a reconfigurable manufacturing system. To illustrate the approach decomposition framework of FR-PI along with path dependencies is developed.

b) To formalize and facilitate the evaluation of the PIs, FBS approach is applied. The approach is modified and adapted to the particular context of RMS design process. In our proposed framework, Axiomatic design (AD) principles are employed to develop a framework for carrying out the design process of RMS. The deployment of FBS approach in the design process has allowed us to integrate the concept of the comparison of desired and achieved objectives.

c) The paradigm of RMS makes it mandatory to have an information system that has a common knowledge base. In this article we have discussed the use of ontologies for knowledge formalization and interoperability of information. The usefulness of ontologies for data formalization and sharing, especially in an open manufacturing environment is discussed. We haveve presented the utilization of a manufacturing upper ontology, aimed to draft a common semantic net in manufacturing domain, with the design methodology for a reconfigurable manufacturing system. We have illustrated the compatibility and applicability of MASON with the design of RMS based on FBS approach.

The design of RMS is proposed to be done in two phases. The first phase consists of generation / design / synthesis of the solutions: definition of the functions with respect to the requirements and the transitions from the functional to behavioral and finally to structural domain.

Chapter 3 focuses on the transition process from the functional to the structural domain via system behavior. These transitions are carried out with help of a design algorithm. Design solution space is explored and possible process plans along with their kinematic configurations are generated. Each of the process plan and kinematic configuration set represents a design solution. In order to initially select a feasible and later an optimal solution, these possibilities need to be evaluated with respect to time, cost, quality…

Chapter 4 deals with the evaluation of the design solutions with respect to quality based on machining tolerances. Design configurations are represented in graphical form and their compatibility to be evaluated by tolerance analysis approach using small displacement torsors is demonstrated.

Chapter 3

F-B-S transition: Generation of Process Plans and Architectural Configurations of Manufacturing Systems

Chapter 3

F-B-S transition: Generation of Process Plans and Architectural Configurations of Manufacturing Systems

This research concerns the generation of process plans and architectural configurations of reconfigurable manufacturing systems simultaneously. With the rapid changes in product design and consequently its process plan, a design methodology is required that treats both the links i.e. Product-Process and Process-Configuration of manufacturing system at the same time. The inputs for the proposed framework are not the process plans but the geometric part descriptions of the part family. An algorithmic design methodology has been proposed to generate machining process plans and kinematic configurations. It explores the complete solution space for the particular part group. The application of the proposed algorithm is illustrated by its application on an automotive part having a set of machining features to be realised.

Introduction

In chapter 3, we have developed a design framework for the design of reconfigurable manufacturing system (RMS). This includes the exploration of the complete solution space by the generation of process plans and their corresponding kinematic configurations. The objective of this chapter can be related to the activity “A3” of the IDEF0 activity diagram of the design framework discussed in chapter 2. This approach should be generic and be applicable to all product families. The fundamental activity in design is decision making: the design of manufacturing system is the process of deciding the values of the decision variables of the manufacturing system. There are numerous methods and tools for the design of manufacturing systems and they fall into three broad categories, namely, operations research, artificial intelligence and simulation. As discussed earlier the RMS design is based on a part family. In chapter 2 we have explained the modelling of the design problem based on FBS approach (Figure 28). Inputs and objectives in terms of functions, behaviour and structure are defined. Now the important question is to how to manage these transitions in order to achieve our design objective.

Figure 28 Application of FBS approach for production system design

Section 1, discusses in detail the existing design methodologies and their applicability vis-à-vis design of RMS. Section 2, details the major design activities involved in the design of a RMS. In section 3 and 4, we have proposed a design algorithm that manages the transition between Functional-Process and Process-Structure domains. Major design steps involved in the design process along with illustration on an automotive part are explained in detail. Consists conclusion and future works are presented at the end

1 Design Process Overview

A RMS and its most important component, reconfigurable machine tool (RMT) is designed to process a given family of features and is constructed from a set of standard modules. A RMT is a machine that is specifically designed to handle product variants within a specific part family (Katz 2007). The RMS composed of RMTs will have a specific kinematic configuration and a set of machining tasks that can be performed on them. These sequenced machining tasks to realize the part family are called process plans. In the following sub sections an overview of the state of the art is provided.

1.1. Determination of kinematic configurations

A methodology for designing reconfigurable machine tools (RMT) (Moon and Kota, 2002(a), Moon and Kota, 2002(b)) takes a set of functional requirements and a set of process plans as the input and generates a set of kinematically viable RMTs to meet the given specifications. A RMT will have a family of machining feature from the outset of the conceptual design. As shown in Figure 29, the synthesis of the RMT starts with the machining needs and information about the current configuration, unless the design is for a brand new machine. In this case, there will be no information on the current configuration. The machining requirements, captured in the machining features, will drive the RMT design. The machining features include the tool path, machining parameters, and work piece information. The set of machining features and machine configurations are the inputs for the RMT design process. According to Moon, during the RMT design process, a designer or design team will do the following:

- Interpret the requirements and figure out what is necessary to be given in the operation plan.
- Select the reference machine design using the pre-compiled database, which is based on the configuration information and the required motions.
- Build the function-structure graph using the motion requirements and the selected reference design.
- Complete the connectivity graph by searching the available machine modules.
- Complete the solution graph by imbedding the function-structure graph into the connectivity graph.

All the possible paths in the solution graph from the work support to the tool are the kinematically viable solutions. The designer then compares the configurations to the selected evaluation criteria. The key to this approach is the unified modelling of machining requirements, machine modules and machine tools.

An essential RMT design task is to determine the required motions and their parameters. Since the input information includes a set of operation plans, which are the family of machining features including machining operation types, cutter locations, and process plans, the first step in RMT conceptual design is to interpret the given information. The next step is to map each of the kinematic functions identified in the previous stage. Function assignments are carried out and the function structure graph will be determined for given set of operations. The required motions, determined in task clarification and the base position, are the functions to be assigned. To accommodate the machine tool design practice, the function mapping also uses the library of commercial machine tools' function structure graph. The possible combinations are compared with the function structure graphs in the library and selected.

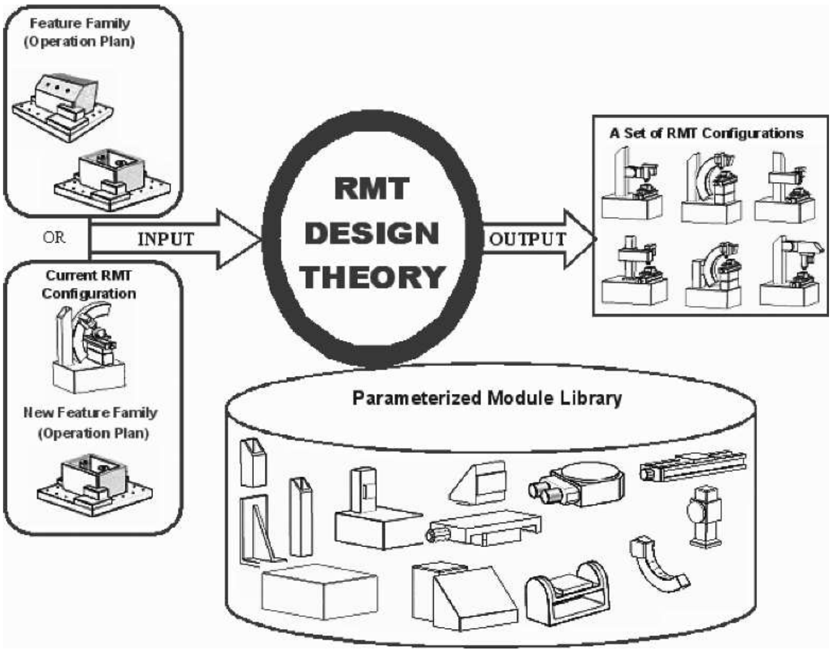


Figure 29 RMT Design Process (Moon et al, 2002)

"Li Chen et al" (Chen, 2005) presented a feature-based method for selecting an optimal (minimum yet sufficient) set of modules necessary to form a reconfigurable machine tool for producing a part family. As also briefly discussed in chapter 2, the method consists of two parts. In the first part, a feature-module database is created to form a selection space, where the machinable geometric features identified in STEP (Standard for the Exchange of Product model data)(STEP-ISO 10303, 1998) are defined as functional requirements (FR's) and the structural component modules derived from the conventional machine tools as design parameters (DP's). An inner FR-to-DP mapping mechanism within the database is based on the "Membership Grade Matrix" which defines matrices to quantify the degree of association between a FR and a DP. Within the confines of the selection space built upon this FR-DP database, the second part of the method again involves a two-step procedure for module selection. The first step is to select the modules from this space to construct all the required individual configurations of the reconfigurable machine tool. The second step is to maximize the number of common modules among the originally selected modules through re-selection. Nevertheless, the design methodology concludes that the successful design of a RMT rests on the premise of a proper set of available machine modules from the parameterized module liberary.

From the above discussion we can conclude that conventional approaches for the generation of kinematic configurations of a RMS take functional requirements and a set of process plans as inputs to the design methodology. Also they require a particular module library containing a set of modules that can be associated to different machining operations. Their output is generation of a set of kinematically viable configurations that meets the input design specifications (Lenders et al, 2001). The machine tool structure can be represented in a kinematic chain-like diagram that shows the machine's axes of motion and degrees of freedom (Bohez 2002).

One very important distinction between the conventional design methodologies and the one proposed by us is the difference in inputs. Firstly the existing approaches address either process plan generation or structural configuration generation, but not both simultaneously. Generation of structural configurations is based on the inputs functional specifications and process plans. The conventional design process inputs/outputs for the generation of kinematic configurations of RMT are shown in Figure 30.

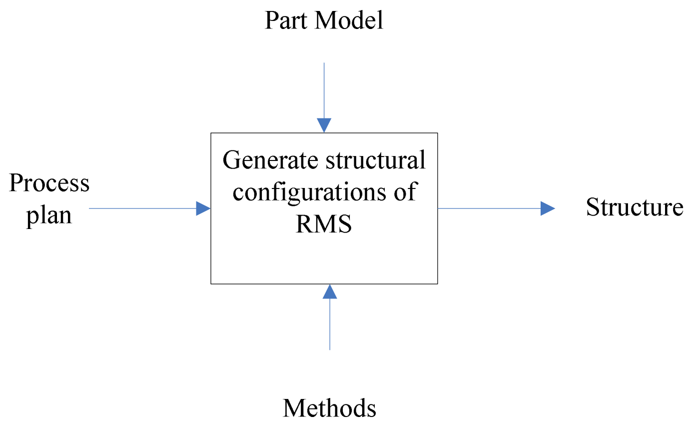


Figure 30 : Conventional RMS design inputs/outputs (Moon et al, 2002)

More recently Shabaka and ElMaraghy (Shabaka, 2007), proposed a methodology for the generation kinematic configurations based on product features. The approach proposes the selection of different types of machines and their configurations to be produced.

The design transforms a given description of machining tasks to perform (process plans) into machine tool capable of performing these machining tasks. This leads us to the all important question of generation of process plans.

1.2. Process Plan Generation

The process plans and planning functions are important links between the features of various generations and variations of products / product families and the features, capabilities and configurations of manufacturing systems and components throughout their respective lifecycles (Halevi, 1995; ElMaraghy, 2009). The process of determining the sequence of operations for manufacturing a part from its design specifications is called "process planning" (Tollenaere, 1998; El Wakil, 1989 and Wang, 1991). Process planning is one of the first activities which bridge design and manufacture. The process domain is represented by spelling out / listing all the required machine operations, their precedence relationships, required degrees of freedom and the probable directions of machining.

Process planning is one of the first activities which bridge design and manufacture. Two approaches to generate process plans are currently used and a synthesis of these approaches and tools used is given in Figure 31.

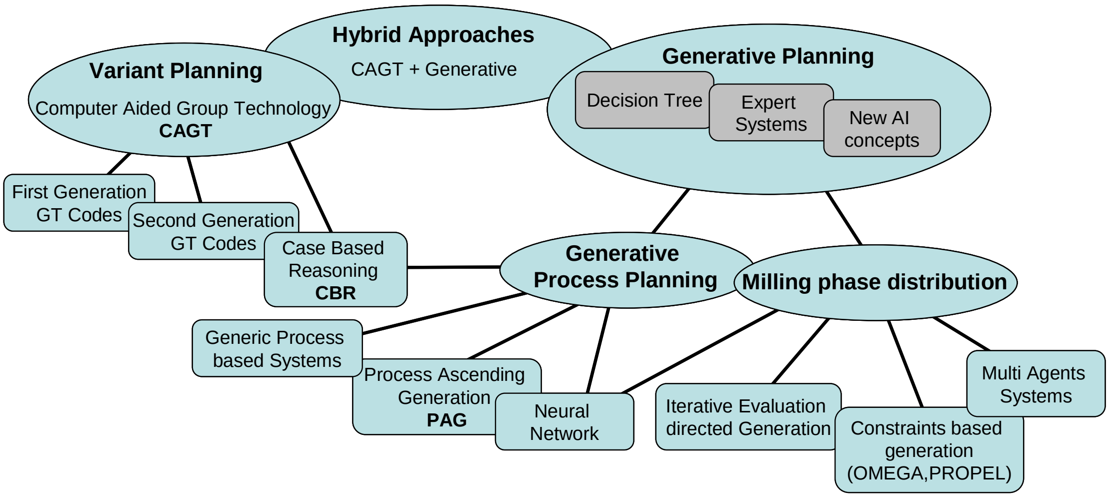


Figure 31 : Milling plans generation concepts (Villeneuve, 1998)

First, there is the variant process planning based on alternative cases. All parts already designed and machined in the company are categorized according to their morphology and dimensions, process plans or other intrinsic characteristics considered relevant and discriminating (Gallagher, 1986). When a new part is designed, it is then possible to find all similar cases and thus to select the corresponding plan (Anselmetti 1994, Chang 1990). However, the use of such a method requires tremendous capitalization of the know-how of company's process planners (about 5 to 7 years of capitalization to be effective according to (Bernard 2003)). In addition, several other difficulties exist: the durability of plans and technical solutions produced the lack of flexibility (it is impossible to adjust one routing if the part to be performed differs locally from the saved reference) and the subjectivity of the part coding. This approach, in spite of the sizable time needed to capitalize knowledge and know-how, is really effective in performing generic plans.

The second approach is the generative approach; it does not retrieve and modify an existing process plan but rather consists of generating one when a new part is designed. Furthermore, this method does not capitalize the problem and its solutions (the machined artifact and its process plan) but rather capitalizes the method and operations needed to find a solution. In generative process planning, process information of a part is used to construct a process plan which optimizes the manufacturing process and generates the required part programs to machine the part. Among the numerous solutions of this approach, one can mention: artificial intelligence software systems (for example: PART (Van Houten et al, 1989) or PROPEL (Brissaud, 1992), generic process based on systems (one machining feature is associated with the entire process needed to machine it (Elmaraghy H. A. and Elmaraghy W. H., 1993; Park, 2003), and solutions using decision tree method (Ordered and hierarchical list of rules). Feature based process planning (Ho, 1997) and PAG (Process Ascending Generation) is also a concept which complies with the generative approach (Villeneuve, 1993) and gives solutions in the form of graphs. An integrated manufacturing process planning framework which includes process planning activities and integration with other application systems has been proposed by Ming et al (Ming, 2008).

Within these diverse approaches, we have reviewed three approaches: the generation of process plans by experts system, the approach by constraint satisfaction and reconfigurable process planning. These process planning methods are discussed with a view to find their compatibility with our stated objective of RMS design.

1.2.1 Generation by expert system

As a result of the work by J. Lederberg (kindsay 1967), DENDRAL, appeared during the 1960s. It was generally employed to address the classification problems or decision making problems. The first expert system dedicated to process plan generation, GARI, was developed in the 80's by the ITMI of Grenoble (Descotte 1981). Since then a lot of prototypes have surfaced and applied for process plan generation (Kiritsis, 1995). PROPEL, which was created for Giat industries and PART was utilized by Bosch and Phillips, can be cited as two examples.

The expert system consists of two main elements:

- **Database**: It is further divided in two sub elements
    - **Set of tasks**: It is the work memory of the expert system. It includes: the set used variable, the user response to questions by the tool and the deductions by the inference engine.
    - **Set of rules**. It capitalizes on the knowledge base of the expert system. The task set is the list of works performed by the expert system. These rules are formalized in the form of If<condition(s)> Then<conclusion(s)> or a new conclusion added to the set of tasks.
- **Inference Engine**: An inference engine allows inferring the new knowledge starting from its own database. It is this part with performs the reasoning task.

1.2.2 Selection by constraint satisfaction

The constraint satisfaction problem is the second approach which is analysed for the generation of process plans. It was interesting because it is nearer to the design problem in which numerous constraints, demands and norms are required to be respected. We were logically interested in the approach for the generation of the process plans or rather the selection of the process variables considering a set of constraints.

The constraint satisfaction approach (CSP) (Waltz, 1972) appeared in the 70s but only really emerged in the 90s. Contrary to the formal calculations which transform the constraints so as to obtain the values of the variables, CSP does not act upon the constraints but rather attempts to reduce the definition domain of the variables. This reduction of definition domain is very interesting for combinatory problems e.g. planning and resource allocation, logistics, design and fabrication. The method CSP is defined by:

- The variable domain: they are the variable types i.e. Real, Symbolic, Boolean, Rational and Similar.
- The constraint type, which can be numeric (equation + in equation), boolean, similar or type. The constraints can also be symbolic, algorithmic or formalised in the form of tables.

A constraint satisfaction problem corresponds to a set of variables from the definition domain and a set of constraints that forms a link between the variables. This approach was already applied for the generation of process plans in works PROPEL

(Brissaud, 1992) or OMEGA (Sabourin, 1995), principally to resolve scheduling problems and allocate machining resources.

In our work framework, we have applied the CSP approach to generate the machining process plans. CSP allows to search all the solutions i.e. “enumerate” them. In the method a constraint in general terms is a relation between the mathematical variables. This relation can be numeric, symbolic, boolean ... A CSP method is defined by the variables or constants (integers, real...) and the constraints (conditions, values of the function...). The method proceeds in two steps i.e. reduction of the definition interval of each variable and the propagation of constraints through each definition interval of each variable.

An application of CSP approach using constraint explorer® (Zimmer et al, 2004) to our objective of RMS design was carried out (screen copy is given in Figure 32).

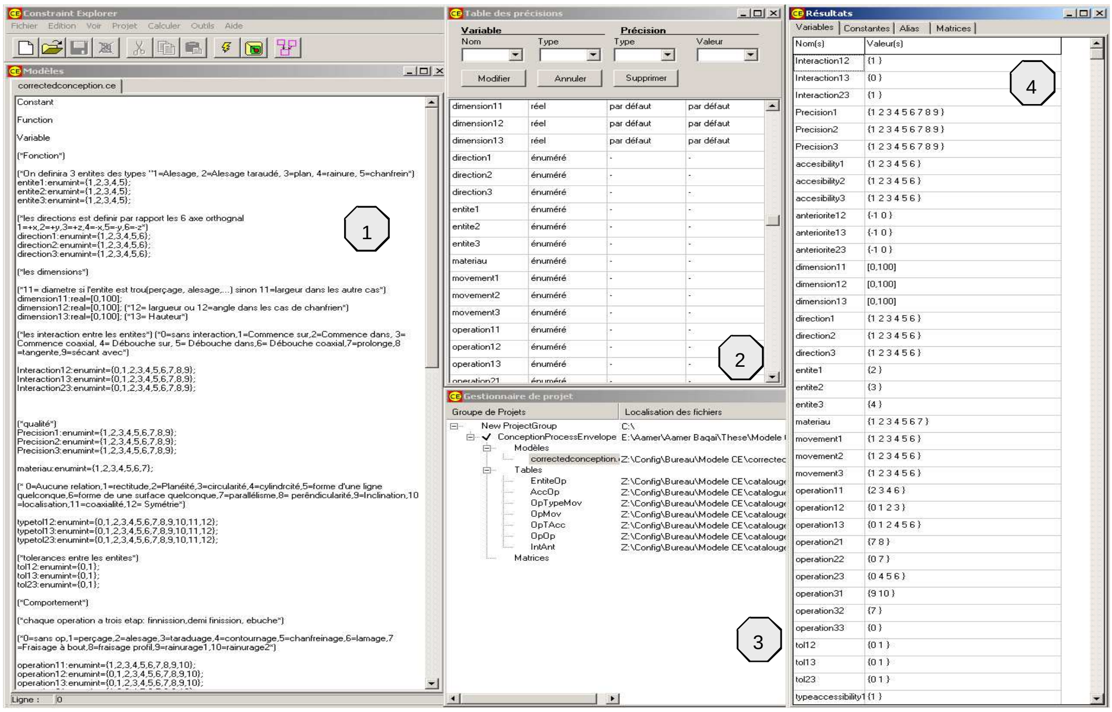


Figure 32 Modelling of the design problem as a CSP

It includes definition of the manufacturing constraints and design variables, shown in zone 1 and 2. Machining knowledge base is attached in the form of catalogues in zone 3. Finally generated results are enumerated in zone 4, representing machining process plans. For the application of CSP, the features must be realized by machining operations; the constraints relative to the compatibility between feature and the operation directions, dimensions, topological interactions ... the list of operations, precedence, accessibility, and movements ... cause the domain to reduce. However, further development of the design problem resulted in difficulties pertaining to dynamic process variables.

Following an implementation of the transition F-B (feature – operations), we have concluded that it would be difficult to automate the transition B-S (operation – kinematic configurations) for the propagation tool, as the type and number of variables describing the structure is not fixed. It changes as a function to the values of variables describing the B (machining operations).

1.2.3 Reconfigurable process plans.

Understanding the type of the manufacturing system affects the method or approach of process planning, which is an important step to create relevant plans. Traditionally, in computer-aided process planning (CAPP) systems, when generating process plans, the manufacturing system components were considered static and only one process plan is developed. A static system has a fixed configuration, e.g. dedicated manufacturing system (DMS), which in turn implies fixed capability and capacity. In the past decade, research was carried out for developing CAPP systems that generate alternative process plans that suit the dynamic nature of such manufacturing systems as flexible manufacturing systems (FMS) and RMS. Flexible process planning was introduced to handle product variability, hence the need for developing alternative process plans. Flexible or non-linear process plans are capable of representing alternative processing sequences and manufacturing resources (Shabaka, 2007).

Reconfigurable process planning (RPP) approach has also been proposed by H.A. Elmaraghy (Elmaraghy, 2006(a); Azab and ElMaraghy, 2007a). This approach deals with the variations in process plans as a result of changing parts and products. Changes in parts might require different machines assignment and thus increased or decreased capabilities. In case of an existing machine reconfiguration, RPP proposes that the part family nearest to the new part, would be identified and its composite parts and master process plans are retrieved. Missing features and operations are removed. Integer mathematical models and mathematical programming for reconfiguring the macro level process plans were formulated and applied to the process planning problem. Reconfiguration of precedence graphs is done by inserting / removing features / operations iteratively.

Two criterions were used in RPP. First, the parts handling and re-fixturing time, when no value is added, is minimized to arrive at a process plan that minimizes the extent of reconfiguration. Secondly a process plan Reconfiguration index, which measure the extent and cost of changes was added. RPP deals with variations in the process plans as a result of changing parts and products. Changes in the process plans might require different machines assignment, depending on the available machines and their capabilities. Changes in machines, would trigger changes in process plans to utilize and benefit from these new capabilities. RPP supports process planer's decision making regarding the machine assignment/selection and sequencing the activities at the initial stages of manufacturing system design.

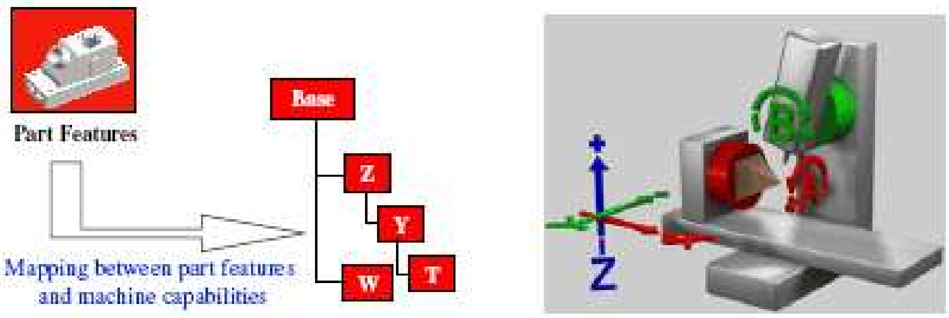


Figure 33 Mapping between part features and machine capabilities in reconfigurable process planning (El Maraghy, 2006(b))

1.3. Summary and Remarks

From the above discussions, it is evident that for the generation of kinematic configurations, both functional specifications and process plans are required. The generation of process plans weather with the conventional approaches or using reconfigurable process planning, requires functional and geometric specifications along with the knowledge of the target machine configuration as shown in Figure 34. In case of RMS design framework, the process plans and the configurations change as a function of the changes in the functional requirements.

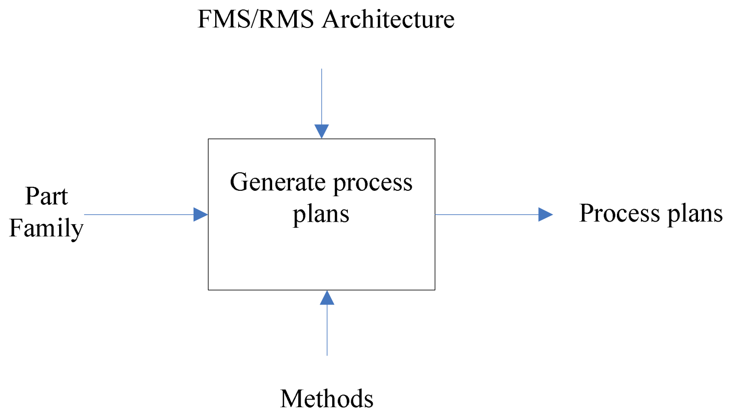


Figure 34 Process planning approach (Halevi, 1995, Shakaba, 2007)

Thus in order to have a generic methodology for the design of a RMS, which has no particular product family in mind, requires the capability of to generate both process plans and kinematic configurations. This methodology should have process plans in terms of allocation and sequencing of machining operations and kinematic configurations in terms of machine motion, axis and modules descriptions. More so the conventional approaches of process plan generation based on the identification of accessibility and research of the minimum number of part positions knowing the structural configurations of the machine is obsolete with RMS. For RMS, the process plan approaches should take into account the aspects of multi-spindle and multi structure in parallel.

For RMS design based on a part family the existing approaches need to be complemented. Therefore, one very important distinction between the current design methodologies and the one proposed by us is the difference in inputs. The existing approaches address either process plan generation or structural configuration generation, but not both simultaneously. In our proposed method for the design of reconfigurable manufacturing system, both process plans and their associated structural configurations are addressed together. The inputs are the functional specifications, topological interactions and process knowledge base as discussed in MASON. Generation of structural configurations is based on the inputs functional specifications and process plans. In the context of flexible manufacturing systems the behaviour i.e. process plan is generated with the knowledge of the structural configuration. In our work, the solutions are in the form of tree structures. We have proposed an algorithmic approach which is to be explained in the following sections.

2 Design Methodology and Activities

In the FBS based design process, as illustrated in the design process activity diagram of chapter 2 (Figure 24), we have focused on two activities out of five i.e. the generation of machining process plans and machine kinematic configurations ("activity 2 and activity 3"). The inputs for the proposed framework are the geometrical part specifications.

There are numerous tools/methods to model and manage the transitions. They include, modelling the decision variables as a constraint satisfaction problem, modelling as an operations research problem and utilizing the algorithmic approach for optimal decision making. Other methods include multi-agent and expert system.

In order to have an approach completely oriented towards the generation of process plans and their respective kinematic configurations simultaneously for an RMS, we decided to follow an algorithmic and deterministic approach. This approach takes into account the machining constraints which dictate the choice of solution, as in the case of a CSP. Also it benefits and utilizes a knowledge base and rules derived from manufacturing ontology MASON, gives out the machining sequences and other decision choices as in case of expert system for the generation of process plans. In the proposed framework the transition from the initial input of part specification to final output of architectural solutions is governed by using a design algorithm proposed by us.

The integrated algorithmic approach explores the set of possible process plans and at the same time explores the corresponding set of possible manufacturing system configurations to perform each of their generated process plans.

The proposed iterative method (Algorithmic) is directed towards the design of reconfigurable manufacturing systems or dedicated manufacturing systems (for a single part position). The algorithmic approach is applied to three automotive parts, namely, CAI, CDV and CPHC, each having a set of machining features. In the subsequent sub sections each of the two activities are explained in detail and their application is illustrated on an automotive part CAI (Cover intermediate shaft) (Figure 35). The algorithm is implemented by developing an Excel based interface and programming in VBA.

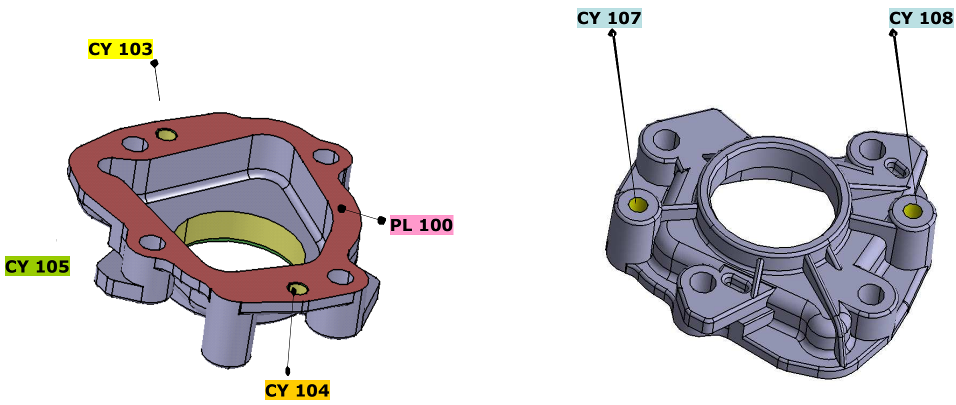


Figure 35 Part to be manufactured CAI

3 Generate machining operations and precedence relationships (A2)

The objective of this activity is to generate a list of necessary operations and precedence relationship between operations (Figure 36). The inputs are a set of geometric specifications for the group of features in the manufacturing part known as part model (part description). These specifications include geometric data (position, accessibility …). The corresponding topological interactions are also provided. These design specifications are subjected to certain rules while utilizing the knowledge base in the form of cutting tool chart. The outputs are the machining sequences and precedence relationship matrices. Each of the above mentioned input is explained in detail in the subsequent sub-sections.

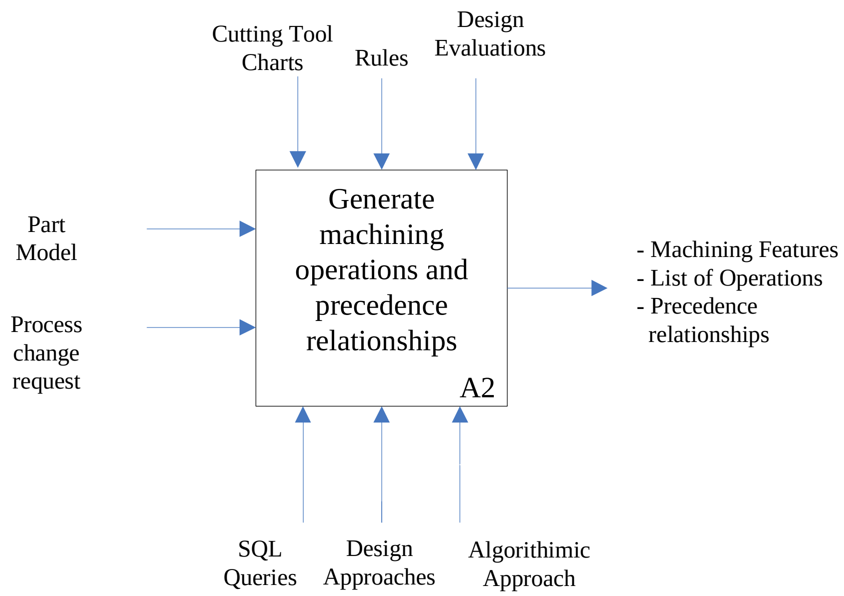


Figure 36 Activity 2

3.1. Machining feature

The concept of feature came into prominence in the 80s, as an intermediately between the part descriptions and manufacturing plans. To automate the machining process plan, the feature concept is pertinent where it supports the problem complexity, which is intimately linked with part model, technological database and the formalisation of the expertise in manufacturing. However, as the feature concept is employed in different domains and with different steps in the product life cycle, a feature is perceived in a different manner by each domain.

Features are defined as generic shapes with which design and manufacturing engineers associate certain attributes knowledge useful in reasoning about the products (Zhang, 1994). Figure 37 illustrate that with a simple bore hole, there are three point of views associated. The geometric view identifies a cylinder; the manufacturing view identifies a drilling operation and the designer view, associate with this feature a product life cycle.

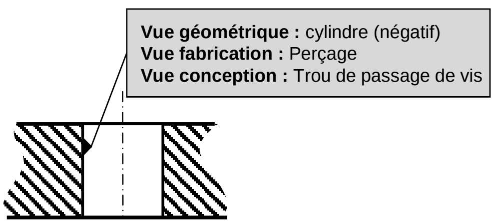


Figure 37 Different point de views of a boring operation (GAMA, 1990)

Here the manufacturing ontology MASON provides the necessary knowledge base and spells out the essential information required for the definition of a manufacturing feature. Graphically the integration of MASON with the machining feature concept is show in

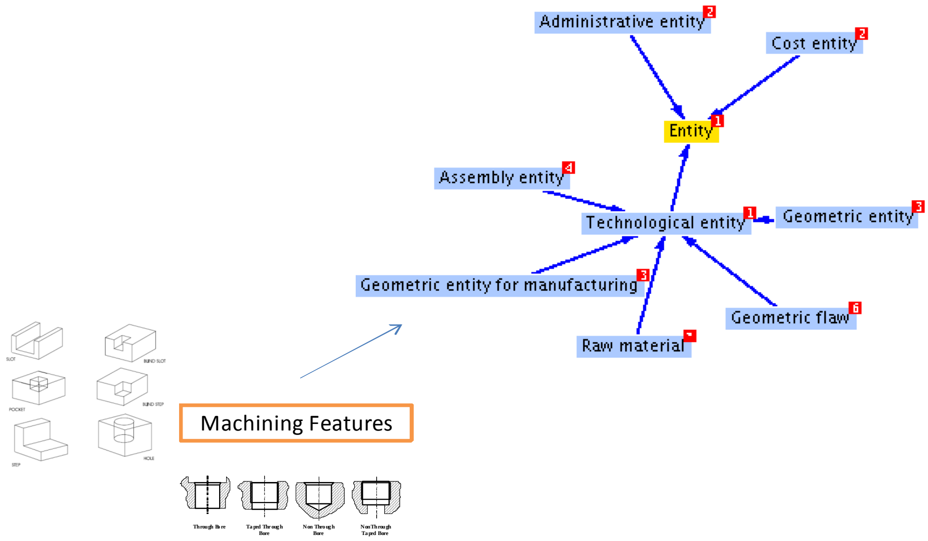


Figure 38 Machining feature concept in MASON

Current process planning systems, such as modern CAD-CAM software packages, deal with the use of features (Shah, 1994). The current status of this concept is drawn in (Cunningham, 1988; Shah, 1988). As a solution of the complexity of current part designs, features perform the breaking up of these work pieces in smaller and easier to handle concepts (Pratt, 1984). Several definitions of these features are available: from those needed to factorize machined parts (Carpenter, 2000) to those used for analyzing welded parts (Case, 2000).

When particularly applied to machining and manufacturing domain, a feature is the combination of a geometrical definition (enriched with technical characteristics) and a semantic definition inspired by process planning engineers. According to the French community GAMA:

A machining feature is a semantic set characterized by a collection of parameters used to describe an indecomposable object relative to one or more activities related on the design and the use of products and systems of production (Tollenaere, 1998). Also, it defines a geometric form as a set of specifications for which a machining process is known. These machining operations are partially independent of the operations for other features.

Machining features can be categorized into four groups (Alpha 1 User's Manual 1992).

- Hole or axial features: These are the features that can be machined by point to point operations. They include plain hole, tapped – hole, counter-sink, counter-bore, counter-drill, etc (Figure 39).
- Simple milling features: This category includes milling features that can be described in standard forms, such as slot, rectangular-pocket, face, straight-step, etc (Figure 40).
- Complex milling features: They include profile-pocket, profile-boss, profile-side, profile-groove etc (Figure 40).

- Compound features: Features in this category consist of multiple features oriented in special relationship, which include rectangular-pattern, circular-pattern and step-bore.

Among the machining features given in the example (Figure 40), simple milling features along with axial features shown in Figure 39 are taken into account in our design framework.

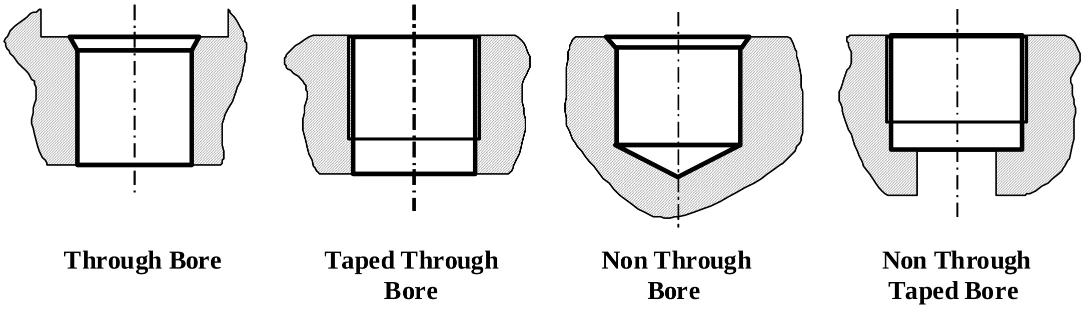


Figure 39 Axial machining features

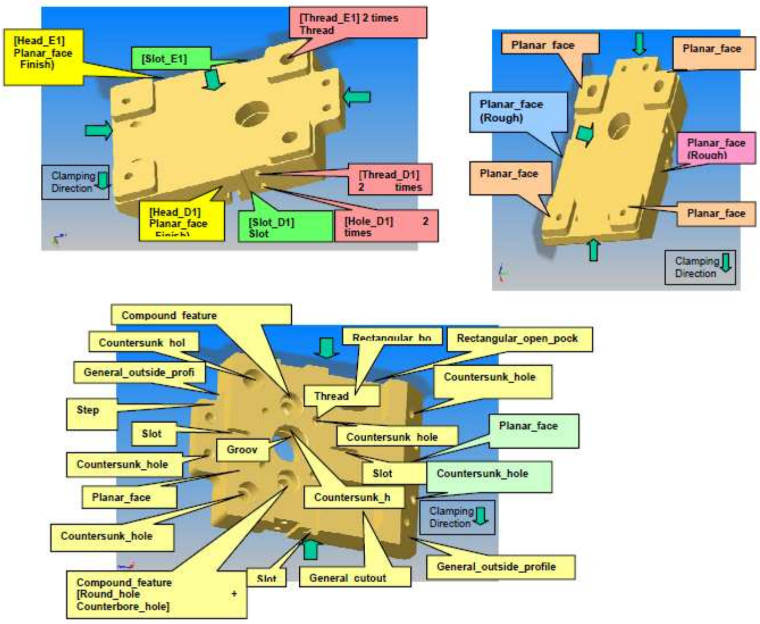


Figure 40 An example of machining features (STEP Application Handbook, 2006)

In RMSs and DMLs the required manufacturing features are mostly axial and simple milling type. In our application of the approach we have chosen products having the above mentioned features.

An example of a manufacturing entity combined with a set of descriptive parameters (geometrical, material and tolerance) is given in Figure 41. Etienne et al, have divided the definition of a machining feature in two parts, i.e. machining enabled geometrical feature (MEGF) and the machinable feature (Etienne, 2006).

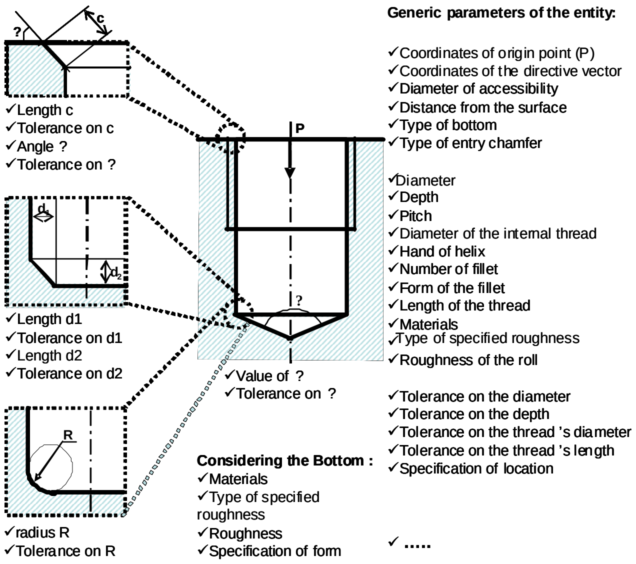


Figure 41 A manufacturing feature (Etienne, 2006)

Their objective was to separate the geometrical and technical information. MEGF was defined as an elementary geometrical semantic set characterized by parameters used to describe an indecomposable geometrical object relative to the process planning activity. The second concept called machinable feature, supports the manufacturing knowledge. In fact, one machinable feature characterizes the possibility of linking at least one Tool/ (Operation - Sequence) couple and a geometrical description from a (Controlled) MEGF.

In the context of the proposed approach, the artefact to be manufactured is required to be decomposed into its constituent MEGFs. They included axial through holes, axial non through holes, coaxial holes, axial threaded holes, slots and planes. However, for the moment stepped holes are not treated. An illustration of the types of features to be treated during the application of the design methodology is given in Figure 42.

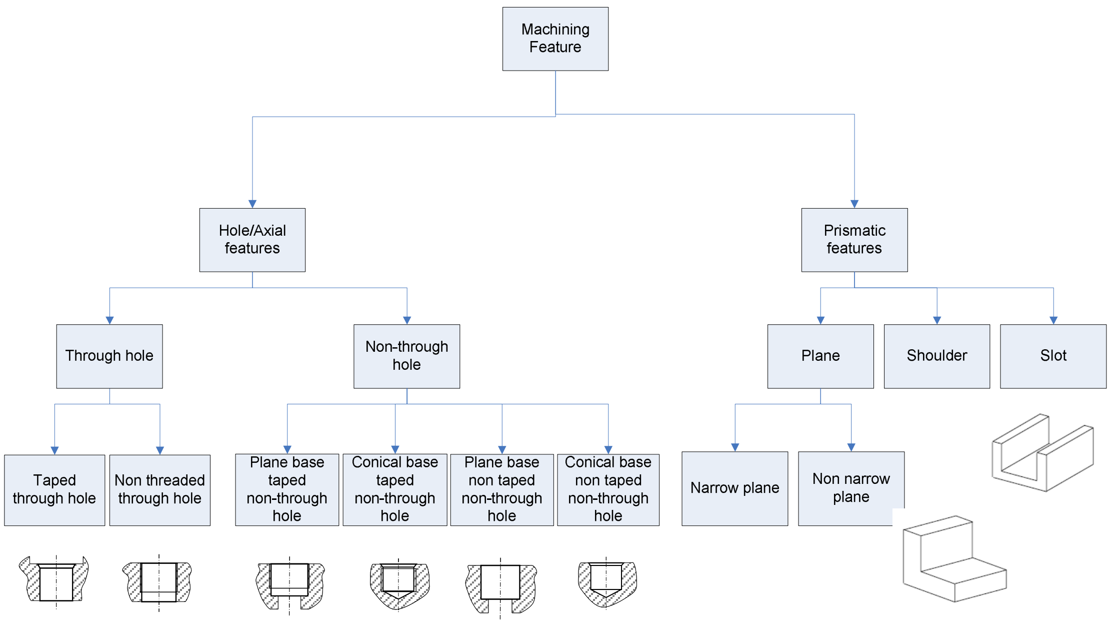
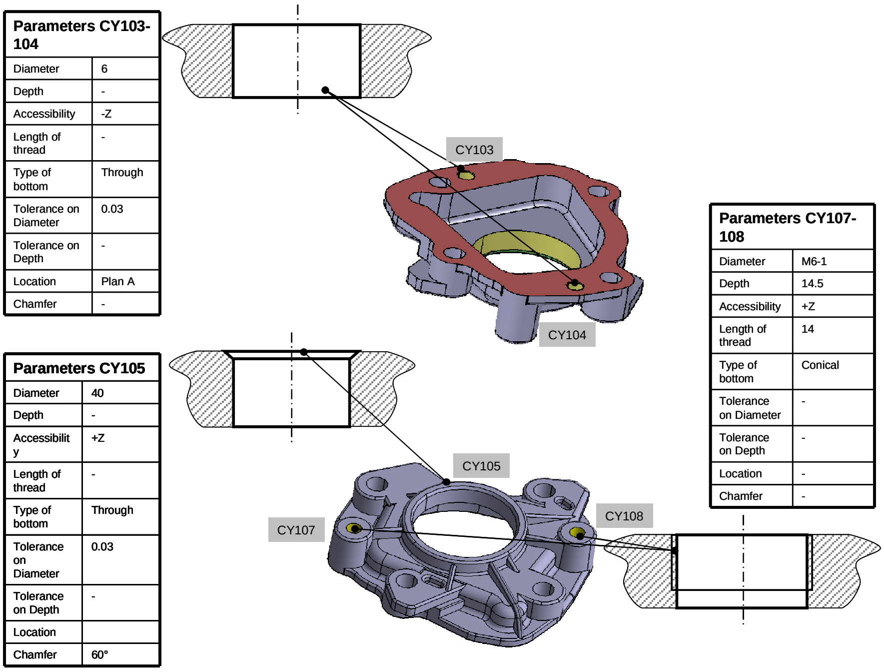


Figure 42 Machining features considered

Each machining feature was detailed like the example in Figure 41. They include geometric relations between characteristic surfaces of a machining feature. Their corresponding technical knowledge i.e. (Operation - Sequence) couple is provided in the cutting tool charts.

3.1.1 Application

In the context of part CAI we have three axial holes, a plane and two threaded holes (Figure 35). From the part drawing their geometrical data is derived and stored in an excel file called "Part Group".



Parameters CY103-104	
Diameter	6
Depth	-
Accessibility	-Z
Length of thread	-
Type of bottom	Through
Tolerance on Diameter	0.03
Tolerance on Depth	-
Location	Plan A
Chamfer	-

Parameters CY105	
Diameter	40
Depth	-
Accessibility	+Z
Length of thread	-
Type of bottom	Through
Tolerance on Diameter	0.03
Tolerance on Depth	-
Location	
Chamfer	60°

Parameters CY107-108	
Diameter	M6-1
Depth	14.5
Accessibility	+Z
Length of thread	14
Type of bottom	Conical
Tolerance on Diameter	-
Tolerance on Depth	-
Location	-
Chamfer	-

Figure 43 Feature CY103, CY104, CY105, CY107 and CY108 in part CAI

It includes the orientation and possible accessibilities. This serves as functional input data for the design methodology. The Figure 43 *illustrates the axial features in the part CAI along with their geometric specifications as stored in file "Part Group".*

CAI

Type	Name	Diametre	Depth	Length	Width	Hieght	Orientation						Accecibility						Position			Angle
							X	(-)X	Y	(-)Y	Z	(-)Z	X	(-)X	Y	(-)Y	Z	(-)Z	X	Y	Z	
Plan	PL100			83,934	82,01						1		1	1	1	1		1	10	10	0	
Hole	CY103	6	14								1							1	10	38	0	
Hole	CY104	6	14								1							1	94	38	0	
Hole	CY105	40	10,56									1					1		42	52	0	
Threaded Hole	CY107	M6-1	14,5									1					1		24	23	0	
Threaded Hole	CY108	M6-1	14,5									1					1		19	23	0	

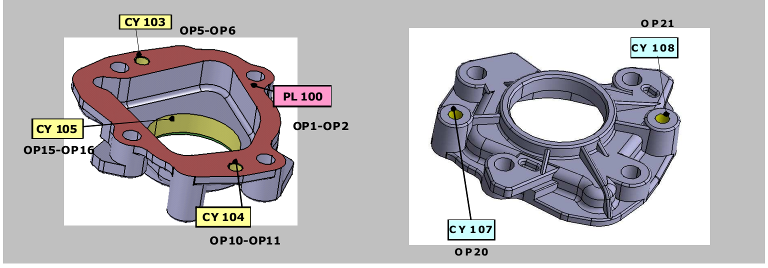


Figure 44 Part to be manufactured CAI

However it is pertinent to mention that the part under consideration does not have any oblique holes or pockets. An overall view of the part model of part CAI can be shown in the screen shot of the file "part group" (Figure 44).

3.2. Topological interactions and relationships

In CAD, two volumetric features are defined as interacting features if their boundaries intersect, so that they share a non-empty, common volume. More than two volumetric features are called interacting features if every one of them interacts with at least another one and all of them form a connected volume. Feature interactions are divided into six categories according to three types of topology variations caused by their interaction: merging of faces, loss of concave edges, and splitting of faces.

However in manufacturing domain we are more interested in topological relations, which permit to characterize a neighbourhood relation between two entities with respect to machining operations. This concept is taken from the knowledge formalism of manufacturing ontology MASON. These topological relations are very much important with respect to the positioning of part and the sequencing of machining operations.

In the case of topological interactions, the part analysis is not only geometric, Figure 45 shows an example of topological interaction between two axial features.

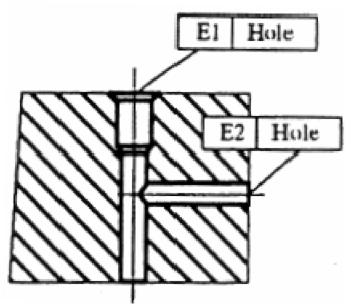


Figure 45 Topological Interactions - example (Villeneuve, 1990)

These interactions also directly influence the determination of operational mode associated to each machining feature. We have defined possible interactions between features like: starts coaxial, emerges coaxial, start on, start in, bore on, bore through, tangent to, not possible at the same time, secant with (planes and cylinders), cross , interference, prolong … etc. These interactions will be used at the time of creation of precedence relationship matrix. An example of these interactions is shown in Figure 46.

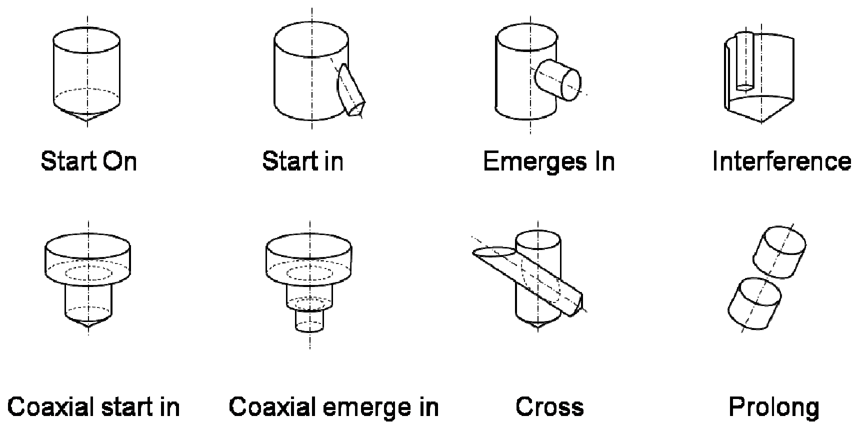


Figure 46 Types of machining feature interactions

3.2.1 Application

*On the demonstration part CAI, we have six machining features (1 * plan and 5 * axial features). Basing on their position with the part their topological relationships are derived and noted on the form of a table as shown* Figure 47. *E.g. feature CY103 bores on plan feature PL100 and is represented by the number associated to it in the relationship list. Each relation is given a numeric code for ease of automatic detection in subsequent manipulations.*

Nom	PL100	CY103	CY104	CY105	CY107	CY108
PL100	0	4	4	0	0	0
CY103	11	0	0	0	0	0
CY104	11	0	0	0	0	0
CY105	0	0	0	0	0	0
CY107	0	0	0	0	0	0
CY108	0	0	0	0	0	0

0=No interaction,
1=Starts on,
2=Starts in,
3= Starts coaxial,
4= Pierce on,
5= Pierce in,
6= Pierce coaxial,
7= Cut through,
8=Tangent,
9= Secant with (for holes)
10= Not possible at the same time
11= Secant with (for plans with holes)

Figure 47 Topological Interactions for the part CAI

3.3. Cutting tool chart

In the concept of cutting tool charts, knowledge formalization and capitalization, the validity range and methods to employ are contained by the solution itself. The cutting tool charts ('Carte de Visite' in French) is a concept defined and implemented by Villeneuve (Villeneuve, 1990; Villeneuve, 1993; Etienne, 2006). These charts look like tables (where production routing specialists can store the validity domain of a machining process (several machining and geometrical parameters are consigned) (Figure 48). This approach however is limited to rigid parameters foreseen by the experts.

Rd

Note : we wrote the Rd medium value in these lists.
The authorized variation percentage on both sides is ± 10%

Part material : 3F , 4F , 4G

Cutting tool	Dt	min. ctD - max. ctD 6 - 8	10 - 12
CAST STELLITE BORING BAR	IT 6	0,05	0,1
	IT 7	0,05	0,1
	IT 8	0,1	0,2

Cutting tool	Dt	min. ctD - max. ctD 12 - 20	25 - 32	40 - 50	63 - 80
CARBIDE TIP BORING-BAR	IT 6	0,2	0,25	0,3	nothing
	IT 7	0,2	0,3	0,4	0,45
	IT 8	0,25	0,3	0,4	0,5
	IT 9	0,35	0,4	0,6	0,8

Figure 48 Carte de Visite (Villeneuve, 1990)

Multiple extensions of this concept have been proposed. F. Langlet, proposed a new implementation of cutting tool charts, so as to render them more flexible by allowing the modification and management of the parameters, more interactive in having a link with the data base interfaced in Access. One of the interfaces is shown in Figure 49 (Etienne, 2003**)**.

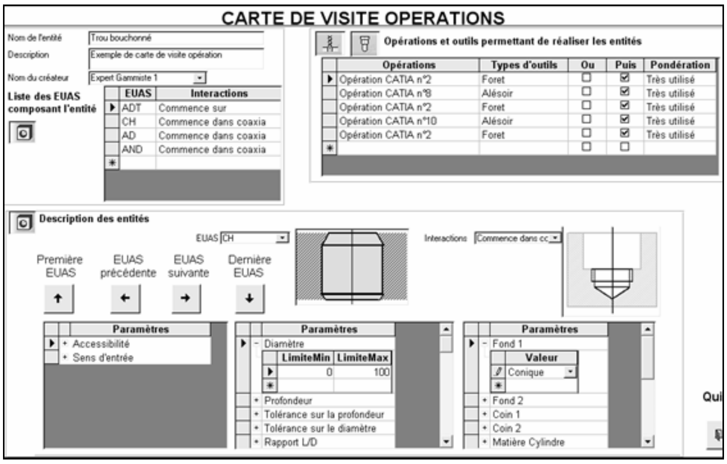


Figure 49 Interface Carte de Visite (Etienne, 2003)

The concept of OSE (Ben Younes, 1994) is an evolution of cutting tool charts. It allows a selection of tools for a given machining feature and can be decomposed in two parts.

- Description of the machining context with the help of three models: the features (entities), the sequences that can be a succession of machining processes, and the functional grouping of tools.
- Association of the three elements so as to transcribe or write down the choice of the process planer.

3.3.1 Proposed Formalism

We have used the concept of cutting tool charts and proposed them to be integrated in the design process due to its ease of use and natural deployment users. For each type of the entity separate cutting tool chart has been prepared. To handle the geometric variations between machining features (within the defined scope of feature types) a number of cutting tool charts are defined.

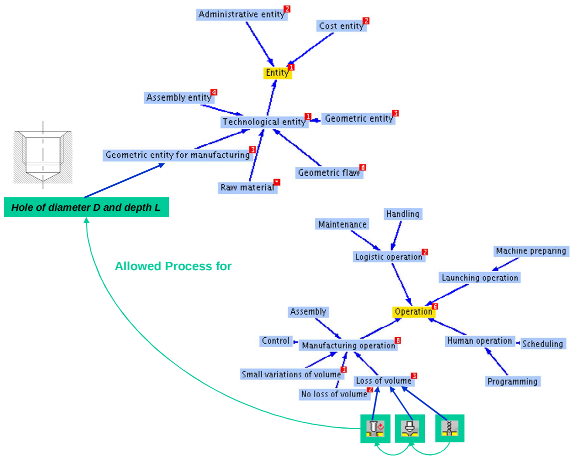


Figure 50 Association manufacturing processes to an instance of feature

Again referring back to MASON, it provides us the necessary taxonomic relationship between a feature and its necessary associated machining operations. According to MASON, to realize each machining feature a set of machining operations are associated to it. This is illustrated in Figure 50.

Based on geometric specification of features and their associated machining operations cutting tool chart for each feature type instances are prepared. They include charts for various axial prismatic features. An example of which is given in Figure 51. Under the associated operation a suggested cutting tool is also given.

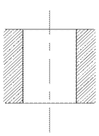
Trou débouchant / Through hole 	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)	Finish Boring R429.900901 301CB H10F	
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)			
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)			
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)			
	10	25	h7	275	10D	Steel and pig iron	Drilling (Factory Std)			
	12	125	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 390 - R390012A16 11L)	Finish Boring (CoroMill 391.38 -1 - T09 A)	
	10	270	IT9	320		All	Rough Boring (CoroMill 391.68 - 8 - T16 A)	Finish Boring (CoroMill 391.38U-1 - 2ATP11A)		

Figure 51 Cutting tool chart for a through hole

Combined with the algorithmic approach, the algorithms can perform process plans, taking data contained in these charts (and thus the know-how of the corporation) into account. Detail cutting tool charts are attached as Annex A.

3.3.2 Processing

For the illustration of the application and the steps involved during the execution of the algorithm part CAI has been chosen. The part under study has three types of manufacturing features to be realized i.e. a plane, three axial through holes and two threaded axial holes. The location of the machining entities along with their possible set of operations required to realize them are shown in Figure 44.

*As an example machining feature CY105 has been chosen (*Figure 44*). To select possible machining sequences cutting tool charts are accessed in the following manner:*

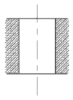
Feature	Diameter D		Tol	Depth L	L Max	Material	Operation	Operation	Operation	Operation
 Trou débouchant / Through hole	12	125	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 390 - R390012A1611 L)	Finish Boring (CoroMill 391.38 - 1 - T09 A)	

Figure 52 Example cutting Tool Chart CY105

- *Based on the part model, machining feature type is selected and stored, which in case of CY105, is a non through axial hole. Corresponding cutting tool chart is accessed.*
- *From the geometric data of the axial entity, corresponding machining sequence(s) is (are) selected.*

  The steps for the selection of the machining sequence are (CY105),

  - *IF the diameter D is 12 < D < 40mm THEN*

  Select corresponding rows of cutting tool chart

  - *IF tol < IT9 and material = val (Material) THEN corresponding machining sequence is selected:*

  In case of CY105 two sequences satisfy the conditions so we select both.

Drilling (Factory Std)	Rough Boring (CoroMill 390 - R390012A1611L)	Finish Boring (CoroMill 391.38 -1 - T09 A)
Rough Boring (CoroMill 391.68 - 8 - T16 A)	Finish Boring (CoroMill 391.38U-1 - 2ATP11A)	

Figure 53 Selected machining sequences for machining feature CY105

- *The two sequences will be used to generate pre-process plan combinations.*

3.4. Machining Sequences

The process plan generation method derives its basics from generative approach. Use of the analogy approach can be relevant in specific cases. For standard borings (for instance: for the spark plug drills, geometry, tolerance, tools and material are standardized), or other drillings whose process plan is well known to designers, it is useless to generate again these mastered processes. In order to prevent our process plan generation method, loosing time regenerating the plan of these mastered processes, experts' process knowledge was used with the concept of sequences.

These sequences are defined by (Sabourin & Villeneuve, 1996) as a series of machining operations that can be interrupted. It represents a series of sequenced machining operations that leads to the realization of a machining feature. The first step is the generation of machining sequences.

It is the first step of the proposed algorithmic approach, where sequence trees are constructed for each geometric feature. A feature can have multiple sequences that can be followed, depending upon the technological constraints. These set of sequences are called pre-process plans. The different branches of sequences are generated from the knowledge base of the experts stored in the "carte de visite". For each type of manufacturing feature its possible machining sequences are given. From these set of sequences, pre-process plans are generated in exploring all the possible combinations.

3.4.1 Proposed formalism

In our case, we define a pre-process plan is a set of machining operations constrained by the precedence relationships which were defined by the topological interactions between features. The process of generation of sequences and its pre-process plans is shown in Figure 54.

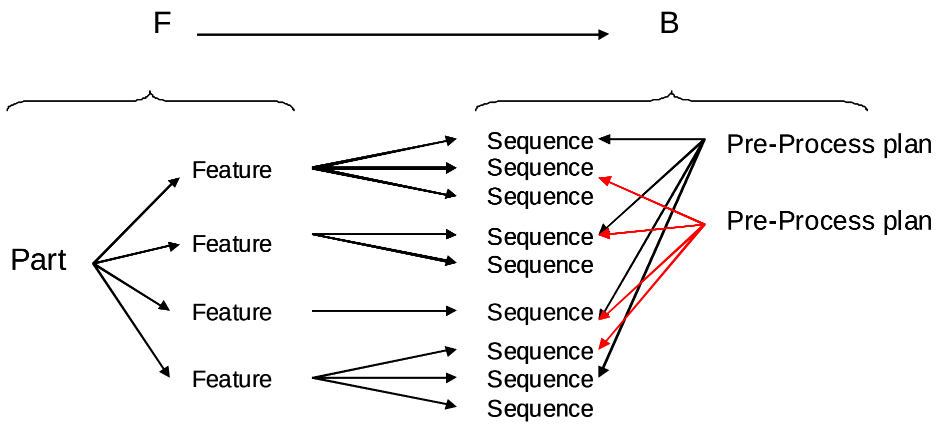


Figure 54 Formalism of machining sequences and pre-process plans

3.4.1 Processing

Figure 55 shows for the part CAI the possible sequence combinations generated using our developed VBA application. In the generated each sequence is numbered, where the first digit represents the feature number and the second digit represents the sequence number. E.g. Seq 12 means second sequence of first feature.

With reference to the selected part CAI, the inputs are in the form of geometric data and topological interactions between the six features. With the help of cutting tool chart all possible alternatives operations are associated with their corresponding *manufacturing entities. This association of machining operation to machining features is subject to technological and topological constraints. Operation lists along with their corresponding tool movement and accessibility directions are generated.*

Possible combinations of different sequences are for the machining features are generated and are known as pre-process plans. Each row of the Figure 55 *represents a pre process plan and is a possibility to be explored by generating precedence relationship matrix.*

Sequence 1 of Feature 1

Feature list

Pre-Process plans

PL100	CY103	CY104	CY105	CY107	CY108
seq 11	seq 21	seq 31	seq 41	seq 51	seq 61
seq 11	seq 21	seq 31	seq 42	seq 51	seq 61
seq 11	seq 21	seq 32	seq 41	seq 51	seq 61
seq 11	seq 21	seq 32	seq 42	seq 51	seq 61
seq 11	seq 22	seq 31	seq 41	seq 51	seq 61
seq 11	seq 22	seq 31	seq 42	seq 51	seq 61
seq 11	seq 22	seq 32	seq 41	seq 51	seq 61
seq 11	seq 22	seq 32	seq 42	seq 51	seq 61
seq 12	seq 21	seq 31	seq 41	seq 51	seq 61
seq 12	seq 21	seq 31	seq 42	seq 51	seq 61
seq 12	seq 21	seq 32	seq 41	seq 51	seq 61
seq 12	seq 21	seq 32	seq 42	seq 51	seq 61
seq 12	seq 22	seq 31	seq 41	seq 51	seq 61
seq 12	seq 22	seq 31	seq 42	seq 51	seq 61
seq 12	seq 22	seq 32	seq 41	seq 51	seq 61
seq 12	seq 22	seq 32	seq 42	seq 51	seq 61

Sequence 2 of Feature 1

Figure 55 Possible pre-process plans

3.5. Precedence constraints

Precedence constraints are designed in machining operations, so that planners have to take scheduling decisions keeping in mind the technological, time and cost constraints. Feasible process plans require precedence constraints to be taken into account. Precedence relationships can be consecutive; firstly one operation always goes behind the other operation, also, there is precedence which obligates one operation to be done before the operation, no matter it follows it or not (ciurana, 2003).

3.5.1 Proposed formalism

For each sequence set, topological relationships are used to define the precedence relationships between different features (Halevi, 1995). However for the precedence between different operations of the same feature, corresponding machining sequence from the cutting tool chart are used in which the sequences contains the order of operations for the realization of the machining feature.

In order to avoid duplication / repetition of the machining operations certain heuristics were required to be defined.

- Case 1: Precedence between two similar operations of the same entity or feature:

  IF OPi = OPj AND Feature i = Feature j THEN

  Machining precedence Prij = 0

- Case 3: Precedence between two operations of the different features:

  IF Feature i <> Feature j THEN

  Refer to feature topological relationship table

  Machining precedence Prij = interaction {Feature ij}, possible values are:

  Prij=-1 (before) OR

  Prij = 1 (after) OR

  Prij = 0 (no-interaction) OR

  Prij = 2 (Not possible simultaneously)

This non simultaneous operation condition (numerical value = 2 in the precedence matrix) is necessary due to the possibility of tool collision during simultaneous machining operations. The necessary condition for simultaneous operations between two holes is:

Distance between the hole > (Dia1+Dia2)/2 + factor of safety

As in case of part CPHC (Figure 56), machining operations on features CY117 and CY118, cannot be performed at the same time due to their interacting diameters, thus they have a topological relationship which forbids simultaneous operation on them.

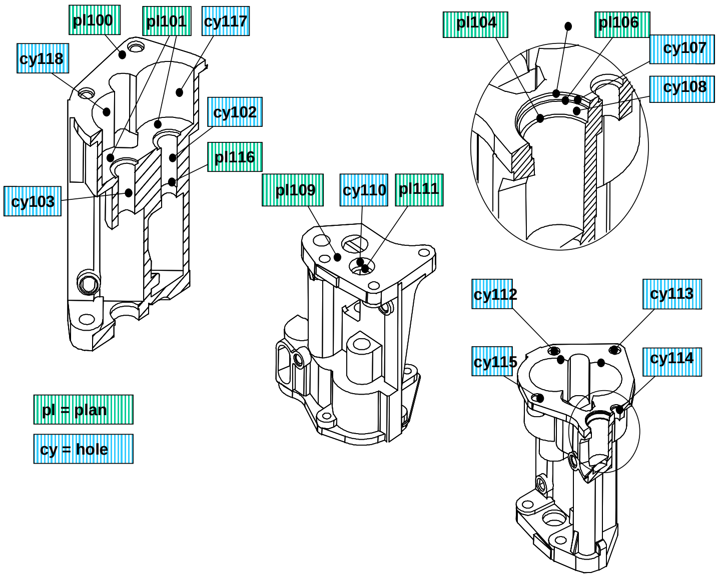


Figure 56 Part CPHC

- Case 3: In cases when the precedence is required between two different operations of the same feature:

IF OP i <> OPj AND Entity I = Entity j THEN

Refer to feature sequence table

Machining precedence {Prij} = {Position OPi} in Sequence of {Feature}with respect to {Position OPj}

If {Position OPi} < {Position OPj} THEN

{Prij} = -1 ELSE,

{Prij} = 1

3.5.2 Processing

Continuing with our illustrative machining feature CY105, procedure for generation of precedence relationship matrix is detailed below:

- *From the pre-process plans sequence table CY105 needs two machining operations to realize it, namely "OP15" and "OP16".*
- *We now define all precedence relationships for OP15 with respect to each of the other features. E.g. with respect to Entity PL100 having OP1*
  - *From the heuristics define in the previous section we have "case 2" which corresponds to the scenario*

    IF Entity I <> Entity j THEN

    Refer to feature topological relationship table

    Machining precedence {Prij} = interaction {entity ij}

- *From the interaction table we have no interaction so a zero is inserted in the corresponding position.*

  $Pr_{1\text{-}15} = 0$

  $Pr_{1\text{-}16} = 0$

For the complete part CAI the precedence relationship matrix is shown in Figure 57. The values 0, 1, -1 and 2 represent no precedence, operation after, operation before and cannot be performed at the same time respectively. The column adjacent to the list of features to be realized, gives the operation number of the machining operation required for each feature. Each number corresponds to a particular operation given in "Carte de Visite" e.g. operation "1" represent rough vertical milling and operation "2" represent finish vertical milling.

Operation List

OP5 follows OP1

Features

		PL100	PL100	CY103	CY103	CY104	CY104	CY105	CY105	CY107	CY108
		1	2	5	6	10	11	15	16	20	21
PL100	1	0	1	1	1	1	1	0	0	0	0
PL100	2	-1	0	1	1	1	1	0	0	0	0
CY103	5	-1	-1	0	1	0	0	0	0	0	0
CY103	6	-1	-1	-1	0	0	0	0	0	0	0
CY104	10	-1	-1	0	0	0	1	0	0	0	0
CY104	11	-1	-1	0	0	-1	0	0	0	0	0
CY105	15	0	0	0	0	0	0	0	1	0	0
CY105	16	0	0	0	0	0	0	-1	0	0	0
CY107	20	0	0	0	0	0	0	0	0	0	0
CY108	21	0	0	0	0	0	0	0	0	0	0

OP20 no interaction with OP1

OP1 precedes OP11

Figure 57 Precedence relationships for part CAI

Precedence relationship matrices for part CPHC and CDV are attached as Annex B and Annex C. The contractual link between the functional requirements and process domain is given by process plans. The generation of a machining process plan consists of chronological determination of machining operations (Chep, 1998). It contains the machining sequences and accessibilities for each entity.

4 Generate process plans and structural configurations (A3): F->B->S

As described earlier the objective of this activity is to generate manufacturing process plans and their corresponding structural configurations. In the preceding sections we have detailed the generation of pre-process plans which represents an initial draft of behavioural aspect. For the generation of the detailed process plans and the kinematic configurations, we have proposed an algorithmic and deterministic approach for this phase. This approach is inspired by the mechanism of controlled enumeration in constraint propagation. The comprehensive iterative method based on the design approach is discussed in this section. The outputs of the "activity 2" become inputs for the "activity 3 (Figure 58)". The outputs of "activity 3" are process plans and their associated structures.

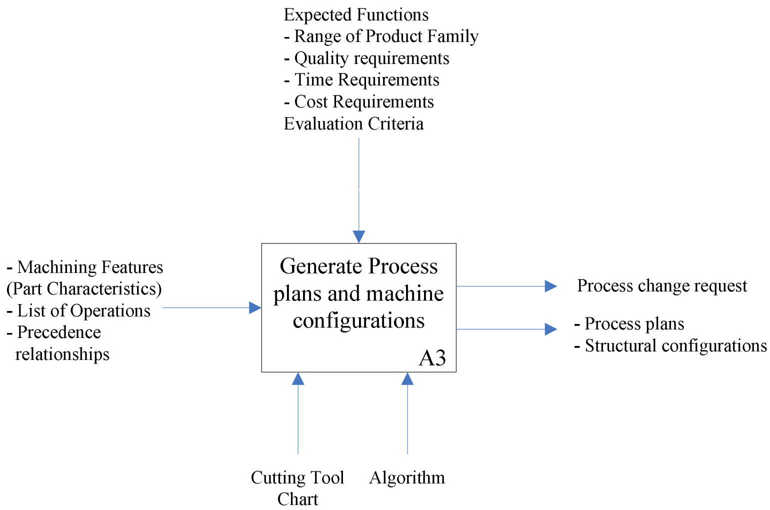


Figure 58 Activity 3

A process plan as defined earlier is an ordered set of machining sequences (Gama, 1990), while a structure is a set of structural elements forming a kinematic chain or elementary machining cells organized between themselves so as to realize a group of parts. In the context of RMS, a post is a collection of structures that can simultaneously perform machining operations from different accessibility directions also to quickly realize a part. A complete machining system consists of multiple posts and each can have parallel or simple structures (D'Acunto, 2007).

The algorithm is based on 6 main steps, each having a particular selection criteria and each step defines a set of solutions along with their associated structures. The possibilities are generated in the form hierarchical tree structures (Baqai et al, 2009). Each branch of this tree represents one / many operations. Each operation realized at a post by a simple structure or parallel structure

These successive steps having conditional loops, generates a tree of possible alternative process plans. Once an operation is associated or assigned to a particular process plan, it frees a series of other operations that can be assigned subsequently on the same structure or simultaneously by having a parallel structure. Each process plan has a particular kinematic chain associated to it which has; machining modules; part holding / rotating fixture and tool change modules. This allows further branching and growing of the alternative process plan tree. The possibility to have a set of branches in parallel, thus multiple operations can be performed simultaneously by different kinematic chains.

The general steps followed by the algorithm are represented in the logic flow chart below in Figure 59.

- Step 0: Initialisation of the first process plan for the first post.
- Step1: Generation of process plan and associated kinematic configuration with operations having zero precedence.

- Step 2: Generation of subsequent process plans of STEP 1 by assigning operations, possible to be performed on the same structure.
- Step 3: Generation of subsequent process plans of STEP 1 & 2 by assigning operations, possible to be performed simultaneously by having one or more parallel structures.
- Step 4: Generation of subsequent process plans of STEP 1, 2 & 3 by assigning operations, possible after a tool / spindle change.
- Step 5: Generation of subsequent process plans of STEP 1, 2,3 & 4 by assigning operations, possible after a part rotation.
- Step 6: explore any other possible solution

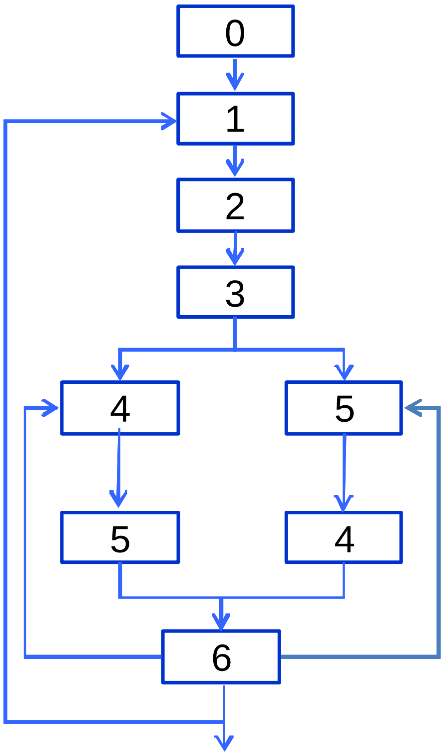


Figure 59 Manufacturing System design Algorithm

4.1. Graphs

Each step of the proposed algorithm for the second activity is detailed in the sub sections below. The illustration and processing is demonstrated on part CAI (Figure 35) for each step. In the subsequent figures, illustrating the implementation of the design algorithm is done by using graphical representation. It includes the machining operations, machining posts and kinematic configurations.

Along with the development of the algorithm, it was necessary to develop data storage formalism. It should store the generated process plans and kinematic configurations in a readable and retrievable form. As the number of operations for each work piece in the product family increase, the possible solutions becomes a combinatory explosion and an automated tree representation becomes difficult. On the other hand it was required to illustrate and identify the different structures working in parallel at first glance.

Different software and programming approaches were considered. One of the methods required an addition of a double line in Excel® each time a new machining operation is instantiated but this was discarded due to the stalling of the application. Thus it was decided to analyze the solution by taking the first possibility until the last operation is attributed to a post. After this we move to next post and study the different possibilities till we reach the last post and all possibilities are documented.

The proposed solution is stored in the form of two tables (Table 2, Table 3). The first table stores and displays the solution any instant in between the process plan generation. It includes:

- machining operation being realized,
- branch no of the assigned operation in the solution tree,
- process plan number,
- post number in the kinematic configuration,
- structure number of the parallel structure on the above mentioned post,
- number of times the algorithm is looped (Step 6 of the algorithm),
- any other branch that is in parallel representing another simultaneous operation on a parallel structure,
- branch precedent.

	N° Branch	N° Process Plan	N° Post	N° Structure
	79	70	4	1
Op Performed	16			
Branch Simultaneous				
Branch Precedent	76	68	4	1

Table 2 Assignment of operations in a Process plans

The values in table 1 are taken from the generated solutions. In the example branch 79 is instantiated representing operation 16. It belongs to process plan 70 and is performed at structure 1 and post 4. On the other hand, Table 3 shows for each possible process plan which are the operations already assigned. It has the process plan number and the assigned branch number. It is helpful in automated recreation of the solution tree, after the complete solution space exploration. Data belong to the example in table 1 is used for illustration.

N° Process Plan	70
N° Branch Active	79
Ops already Performed	1,2,5,10,15,20,21,6,11,16

Table 3 Assigned operations in a process plan

Here the process plans represents two important and individual concepts. Firstly it represents a set of physical elements i.e. structures, posts and tool, spindle change modules. On the other hand it is also a conventional sequencing of machining operations. Now we move towards the actual implementation of the design algorithm.

Before explaining the activity "A3" certain important concepts and their representation in the solution graphs are explained:

- Operations ⟶:

Conventionally a machining operation is referred to as a material removal activity, in which the power driven machine tools are used with sharp cutting tools to take away the part material so as to achieve the desired shape. However in our graphical representation, an operation arc is not limited to metal removal processes. It includes any activity that incurs time, is directed towards the final realization of the part and is required to be performed along with machining operations e.g.: machining operations, tool change operations, spindle change operations, part rotation operations and post change operations. Depending on the machine structure and configuration, each of the discussed operations can be represented with an "arrow".

Parallel axial operations having the same orientation are assumed to be performed together with multiple spindles.

- Structure:

A structure is a set of kinematic modules allowing the displacement of one or more elements e.g. spindle + tool.

- Posts and Start / End of activities on a post ○:

A machining post comprises of one or many machine structures. For a post a single part position is permitted. However, the artefact may be rotated to allow more accessibility and avoid multiple loading/ unloading of part. A post can have multiple parallel structures to allow simultaneous metal removal operations. Depending on the orientation of the machining feature to be realized and the possibility of simultaneous machining, structures are defined. Each parallel structure is assigned a particular accessibility.

- Start / End of an/several activity/activities ●:

It is an intermediate state either between machining operations or any other related activity that is to be performed on the same post. The representation of this intermediate state is very important as it not only indicates the start or end of an activity but also permits to display the necessary precedence relationship between machining activities being performed on parallel structures simultaneously. For the activities that will affect the parallel structures, a "dashed line: -------" is used to connect the activity that it will be performed simultaneously. E.g. in case of rotation of a part during its realization, being performed on parallel structures, it is necessary to indicate the minimum condition before which rotation cannot be carried out. This will be demonstrated later in the illustration on part CAI.

4.2. Step 0

4.2.1 Objective

The objective is to initialize the first process plan and the first structure at the first post. For the 1st iteration all variables like branch number, process plan number, post number etc are initialized.

4.2.2 Processing

As an input to be used in the application of the design algorithm, following classification of the machining operations is carried out.

- Ranking of the operations bases on their anteriority or precedence. (The precedence is defined as a set of operations that must be performed before the one under consideration.)
- Ranking based on the no of operations following an operation (Posterior)
- Grouping based on the similarity of spindle directions with the operation under consideration.
- Grouping based on the alternate spindle directions with the operation under consideration.
- Grouping based on the similarity of feature axis with the operation under consideration.
- Grouping based on the similarity of operation type with the operation under consideration.

For the second iteration all operation already assigned are eliminated and precedence and posterior re-ranking is done.

4.2.3 Illustration

After carrying out the above classification and grouping we have an Excel sheet for each group. They will be accessed during application of the algorithm. To illustrate one of the sheets performing the precedence ranking when applied to part CAI is given in Figure 60. The first row and column are the operations predefined by the pre-process plan for the part. Second row is generated having values showing the order of operation precedence. Machining operations {1, 15, 20 and 21} are found as operations having zero preceding operations. In the second sub table shows a ranking in increasing order of precedence.

Operations

Operation Precedence

Precedence Ranking										
	1	15	20	21	2	16	5	10	6	11
	0	0	0	0	1	1	2	2	3	3
1	0	0	0	0	-1	0	-1	-1	-1	-1
15	0	0	0	0	0	-1	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	-1	-1	-1	-1
16	0	1	0	0	0	0	0	0	0	0
5	1	0	0	0	1	0	0	0	-1	0
10	1	0	0	0	1	0	0	0	0	-1
6	1	0	0	0	1	0	1	0	0	0
11	1	0	0	0	1	0	0	1	0	0

Precedence groups			
1	15	20	21
15	20	21	2
20	21	2	16
21	2	16	
2	16		
16	5	10	
5	10		
10	6		
6	11		
11			

Figure 60: Generation of precedence ranking of operations for part CAI

4.3. Step 1

4.3.1 Objective

The objective of step 1 is to find out that for each of the generated solution already generated, which is (are) the next operation(s) that can be performed on this post basing on precedence and operations posterior to it? However for the first iteration it can be modified to find the operation(s) are having zero preceding operations and maximum following it.

4.3.2 Processing

For the first iteration, this step identifies the first operation that can be performed on the post. It identifies for each generated process plan and corresponding configuration, the machining operations that can be completed without affecting any other operation. These are the operations that have no preceding operation/operations to them. After listing these operations, the operation/operations having maximum operations following it is/are selected from the one already listed i.e. the one having maximum operations "POSTERIOR" to it. Step 1 (Figure 61) can be represented as follows:

- For each generated process plan sort the operations (without the one already assigned) with respect to number of operation precedent to it. This set may be called OPi.
- For each of the generated process plan and configuration, from OPi, select the operation(s) having maximum operation(s) posterior. This set may be called as OPj.
- Instantiation of the selected operation to a process plan, a post and a structure.
- Update for each process plan, the list of already assigned operations and the tables resulting from step 0.

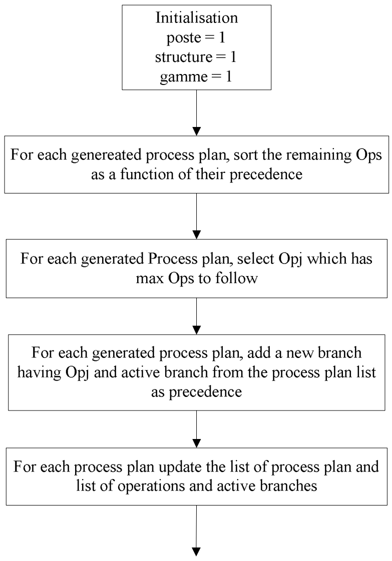


Figure 61 Sequence of sub steps of STEP 1

4.3.3 Illustration

The first step identifies operations {1, 15, 20, and 21}, as operations having zero precedence and operation {1} having maximum operations posterior to it. Thus the first solution has operation "1" at the first post and first structure. In the subsequent figures, illustrating the implementation of the design algorithm, a triangle represents a post and circle represents a start / end of a machining operation.

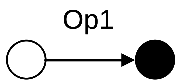


Figure 62 Step 1 for part CAI

4.4. Step 2

4.4.1 Objective

Step 2 finds out for each of the already generated process plan, the operations having zero precedence and which are similar to the operations instantiated in the first step, and to create alternative process plans with them. Similarity signifies that the necessary kinematics to perform the operation i.e. the accessibilities of the features are identical.

4.4.2 Processing

It indentifies operations same kinematics required to realize feature i.e. identical accessibility directions for each process plan. These operations are searched from the generated list of operations having ZERO precedence in STEP 1, thus creating alternative solutions. This step and its sub steps are performed as follows

- For each solution already generated, select the operations OPj from OPi having the same spindle direction, type of operation and axis to the ones selected in Step 1.
- If the result set is empty: proceed to step 3.

- If the result set is not empty: create new alternative process plans with the affectation of operations.
- Alternative solutions are added.

The complete sequence of sub steps for step 2 is shown in the following flow diagram (Figure 63):

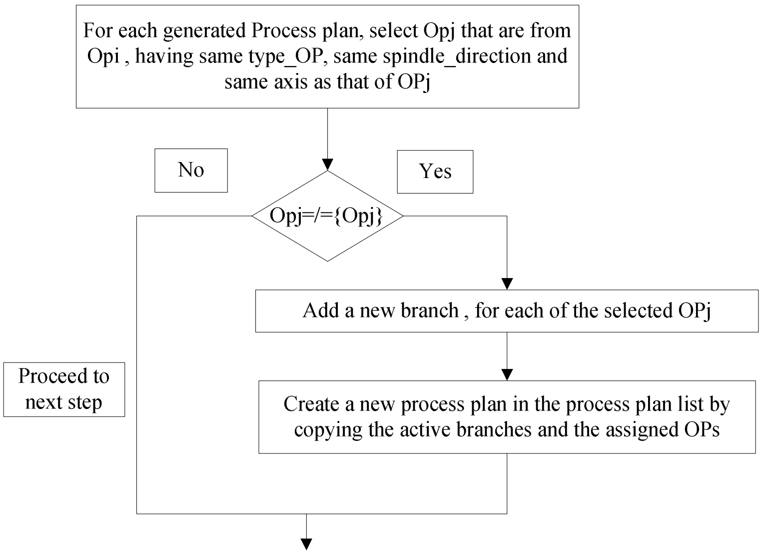


Figure 63 Sequence of sub steps in Step 2

4.4.3 Illustration

Classification based on axis, similar spindle direction and similar operation type is carried out as shown in Figure 64, Figure 65, Figure 66.

		1	2	5	6	10	11	15	16	20	21
1		1	1	0	0	0	0	0	0	0	0
2		1	1	0	0	0	0	0	0	0	0
5		0	0	1	1	1	1	0	0	0	0
6		0	0	1	1	1	1	0	0	0	0
10		0	0	1	1	1	1	0	0	0	0
11		0	0	1	1	1	1	0	0	0	0
15		0	0	0	0	0	0	1	1	1	1
16		0	0	0	0	0	0	1	1	1	1
20		0	0	0	0	0	0	1	1	1	1
21		0	0	0	0	0	0	1	1	1	1

Operation List

OP6 has dis-similar movement axis to OP21

OP15 has similar movement axis to OP21

Figure 64 Group Axis

	1	2	5	6	10	11	15	16	20	21
1	1	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0
5	0	0	1	0	1	0	1	0	0	0
6	0	0	0	1	0	1	0	1	0	0
10	0	0	1	0	1	0	1	0	0	0
11	0	0	0	1	0	1	0	1	0	0
15	0	0	1	0	1	0	1	0	0	0
16	0	0	0	1	0	1	0	1	0	0
20	0	0	0	0	0	0	0	0	1	1
21	0	0	0	0	0	0	0	0	1	1

Operation List

OP6 has dissimilar operation type than OP21

OP20 has similar operation type than OP21

Figure 65 Group OP

	1	2	5	6	10	11	15	16	20	21
1	1	1	0	0	0	0	1	1	1	1
2	1	1	0	0	0	0	1	1	1	1
5	0	0	1	1	1	1	0	0	0	0
6	0	0	1	1	1	1	0	0	0	0
10	0	0	1	1	1	1	0	0	0	0
11	0	0	1	1	1	1	0	0	0	0
15	1	1	0	0	0	0	1	1	1	1
16	1	1	0	0	0	0	1	1	1	1
20	1	1	0	0	0	0	1	1	1	1
21	1	1	0	0	0	0	1	1	1	1

Operation List

OP5 has dissimilar spindle direction to OP21

OP16 has similar spindle direction to OP21

Figure 66 Group Spindle

On part CAI, the application of this step does not generate any alternate solution and so we proceed to step 3 without assigning any new operation. An application of step 2 in the developed tool is shown below and in Figure 67:

From OPj mSpindle to Opj = 1	2	15	16	20	21
From OPj mOP to Opj = 1					
From OPj mAxe to Opj = 1	2				

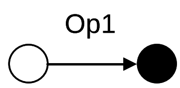


Figure 67 Step 2 for part CAI

4.5. Step 3

4.5.1 Objective

The objective of this step is to explore the already generated solutions the possibility of performing machining operations simultaneously on one or more parallel structures with the operations identified in Step 1 and Step 2.

4.5.2 Processing

This is done by having parallel machine configurations at each post. The criteria for selection of the simultaneous operations are alternative accessibility direction to the operations already assigned from the set of operations having zero precedence.The application sequence of step 3 is as follows:

- From the operations having zero precedence, select the operations that have the alternative spindle direction to the operations already assigned to the post under consideration.
- If the result set is empty: proceed to next step.
- If the resulting operation set is not empty: Subdivide the operations into groups of operations having same spindle direction and type of operation.
- Create alternative solutions by copying the previous process plan and instantiating the operation groups and (one or more) parallel structures (as a function to the number).

The complete sequence of sub steps for step 2 is shown in the following flow diagram (Figure 68):

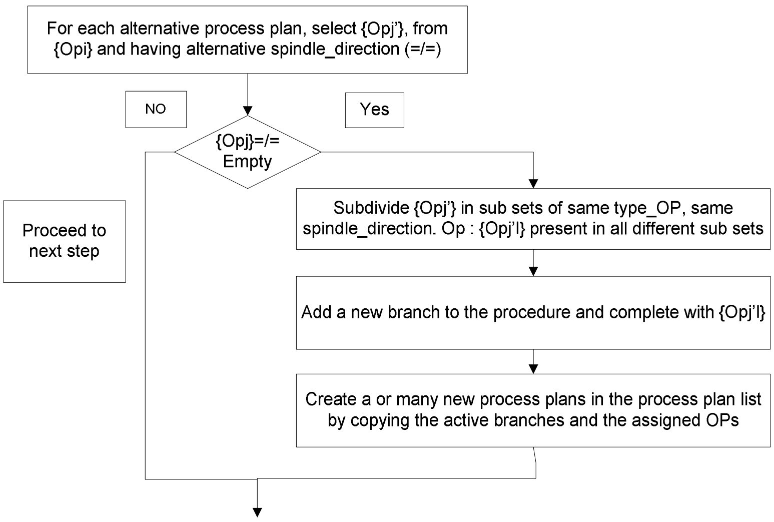


Figure 68 Sequence of sub steps in Step 3

4.5.3 Illustration

For the application on part CAI, from the spread sheet "group Spindle-Alt", operations having alternative spindle directions to operations in OPj were searched.

		1	2	5	6	10	11	15	16	20	21
1		0	0	1	1	1	1	1	1	1	1
2		0	0	1	1	1	1	1	1	1	1
5		1	1	0	0	0	0	1	1	1	1
6		1	1	0	0	0	0	1	1	1	1
10		1	1	0	0	0	0	1	1	1	1
11		1	1	0	0	0	0	1	1	1	1
15		1	1	1	1	1	1	0	0	0	0
16		1	1	1	1	1	1	0	0	0	0
20		1	1	1	1	1	1	0	0	0	0
21		1	1	1	1	1	1	0	0	0	0

Operation List

OP11 has alternate spindle direction to OP21

OP20 does not have alternate spindle direction to OP21

Figure 69 Group Spindle_Alt directions

Result of application of Step 3 is shown below:

Spindle_alt to OPj=1	5	6	10	11	15	16	20	21
From OPi Spindle_alt to OPj=1	15	20	21					

- This resulted in the generation of a set {5, 6, 10, 11, 16, 20 and 21}.
- Further application resulted in two sub groups {15} and {20-21}. Here an assumption is made that similar machining operations on parallel features (having same orientation and accessibility) will be performed with the help of twin spindle, therefore simultaneously (this constraint may be removed if required). Thus the two possible alternative process plans and structures are generated as shown in Figure 70.

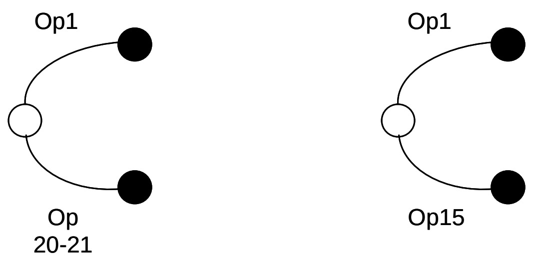


Figure 70 Step 3 for part CAI

4.6. Step 4

4.6.1 Objective

The steps attempts to find for each generated solution via a tool change and/or spindle change. Thus the selected operations will be of the same kinematic type and same accessibility direction to the operations already assigned on the post.

4.6.2 Treatment

Step 4 explores all possible alternatives generated up to step 3 that can be accomplished by a tool and broche change. The sub steps are as under:

- Update the tables generated in Step 0 by removing the operations already assigned from the list of operations. Redefine the precedence relationships. New set of operations OPj'' having zero precedence is generated
- Select from OPj'', operations having similar spindle direction and movement axis to the one already assigned to the structures of the post.
- If the result set is empty: proceed to next step
- If the generated set is not empty:
  - o Sub-divide, based on similarity of operation type.
  - o Alternative process plans and structural configurations are generated by copying the previous plan and associating assign a tool change operation along with the operation group.

The complete sequence of sub steps for step 4 is shown in the following flow diagram (Figure 71):

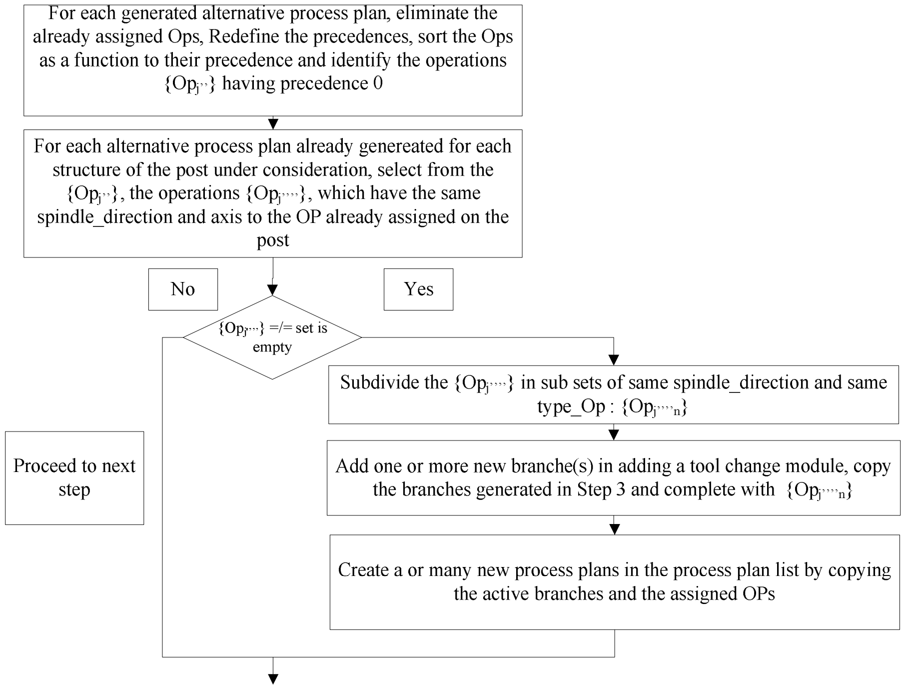


Figure 71 Sequence of sub steps Step 4

4.6.3 Illustration

- Between the two generated process plans we have chosen the one having assigned the maximum no of operations i.e. {1, 20 and 21}.
- Precedence rankings are redefined after elimination the already assigned operations.
- The new zero precedence operation set is {2, 15}.
- Operation set is {2, 15} satisfies the next criteria of similar spindle direction and movement axis to the Operations already assigned to the structures of the post.

Figure 72 shows the sequence of implementation on the developed tool. Two sub groups of operations i.e. {2} and {15} or operations {2} and {20-21} are generated for the two parallel structures on the same post.

Step 4			
OPs already assigned	1	20	21
OPj''	2	15	
Same Spindle and Axis to the OPs already assigned...			
OPj'' – Same spindle to OP1	2	15	
OPj'' – Same Axis to OP 1	2		
{OPj''''_to OP1}	2		
Among OPj'' same spindle to OP20	2	15	
Among OPj'' same Axis to OP20	15		
{OPj'''' to OP20 }	15		
Among OPj'' same spindle to OP21	2	15	
Among OPj'' same Axis to OP21	15		
{OPj'''' to OP21}	15		
Set_OPj''''	2	15	
OPj''''1	2		
OPj''''2	15		

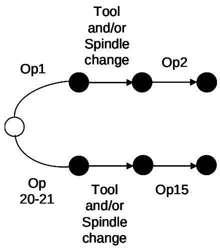


Figure 72 Step 4 for part CAI

4.7. Step 5

4.7.1 Objective

Like Step 3, the objective is to find the operations having alternative spindle directions than the solution under consideration? The generated solutions are explored with the possibility of part rotation. The criterion which allows the possibility of alternative process plans is the existence of a machining operation of same nature to that of the ones already assigned in the previous steps having an alternative accessibility direction.

4.7.2 Treatment

Depending on the structure and machining feature's orientation, a rotation of the piece is proposed after in this step. Details of the sub steps are given as under:

- Update the tables of "step 0" by removing the operations already assigned. Re-define the precedence relationships. A new set of operations OPj''' having zero precedence is generated.
- Select from OPj''', operations having similar alternative spindle direction and similar kinematic type.
- If the generated set is empty: proceed to next step
- If the generated set is not empty:
    - Sub-divide on similarity of spindle direction and operation type.
    - Alternative solutions are generated by assigning a part rotation operation, if required a tool and / or spindle change operation, to the copied plan from the previous step.

The complete sequence of sub steps for step 2 is shown in the following flow diagram (Figure 73):

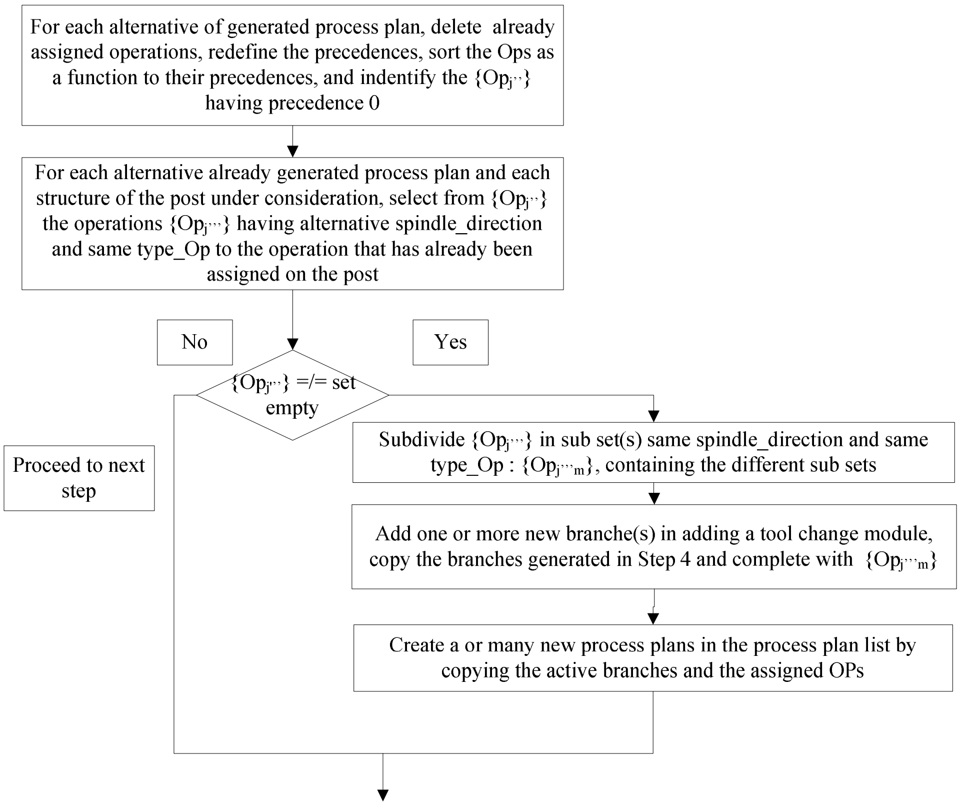


Figure 73 Sequence of sub steps of Step 5

4.7.3 Illustration

- Precedence rankings are redefined after elimination the already assigned operations.
- The new zero precedence operation set is {5, 10 and 16}.
- Operation set is {5 and 10} satisfies the next criteria of similar alternative spindle direction and similar kinematic type to the Operations already assigned to the structures of the post.
- The resultant process plan and structural configuration is shown after adding to the second parallel structure is shown in Figure 74.

Figure 74 shows the sequence of implementation on the developed tool. A group of operations 5-10 is generated and is shown in Figure 74

Step 5					
OP already assigned	1	2	20	21	15
OPj''	5	10	16		
Spindle_Alt and same type_OP and sameType_Kinematic to the Ops already assigned....					
OPj''' having spindle_alt and sameType_kinematic to OP1					
OPj''' having spindle_alt and sameType_kinematic to OP2					
OPj''' having spindle_alt and sameType_kinematic to OP20	5	10			
OPj''' having spindle_alt and sameType_kinematic to OP21	5	10			
OPj''' having spindle_alt and sameType_kinematic to OP15	5	10			
Set_OPj'''	5	10			
OPj'''_1	5	10			

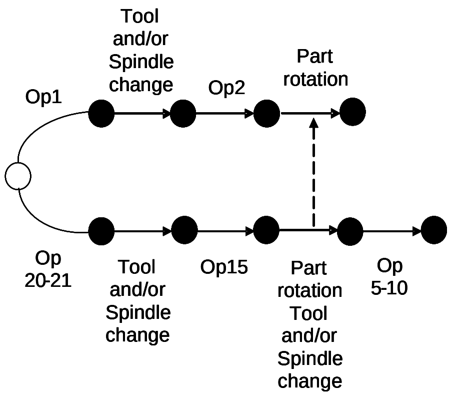


Figure 74 Step 5 for part CAI

4.8. Step 6

4.8.1 Objective

The objective is to explore any other solution possible either by tool / spindle change or part rotation. Step 6 is to explore the complete solution space and assign as much machining operations as possible at the same post.

4.8.2 Treatment

Step 6 performs three tasks at the same time.

- Firstly it attaches the generated solution to alternative process plan tree.
- It returns the possible alternative process plans to step 1, for their continued processing on the next post.
- it sends the alternative process plans through two loops towards Step 4 and Step 5 as shown in Figure 59. The closed loop 4-5 and 5-4 is continued until the generated solution is similar to the one at the start of the loop (no new operation is added).

This Step ensures that all possible solutions for a particular post for all structures have been explored. However care should be taken that for Step 4 and Step 5, the last generated operation is kept for reference instead of the complete list of operations already assigned. A detailed view of step 6 is given in Figure 75.

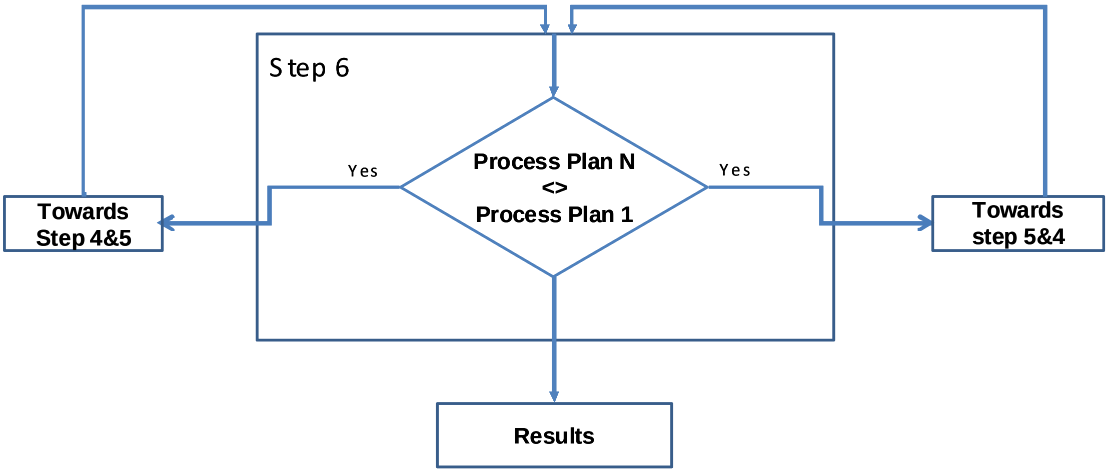


Figure 75 Step 6 for part CAI

4.8.3 Illustration

- For the loop step 4-step 5, step 4 did not result in any new solution
- A part rotation in step 5 resulted in the generation of op set {16}.
- In particular case of part CAI, for the first iteration, first solution was found (Figure 76).

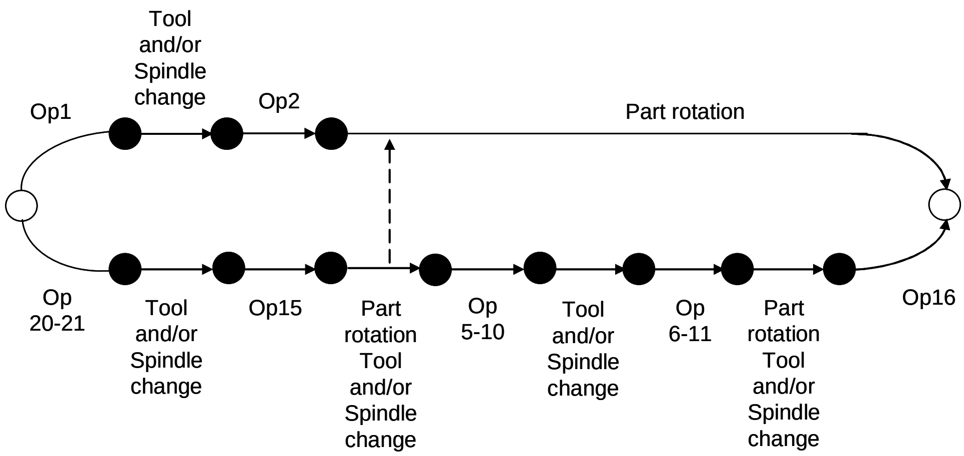
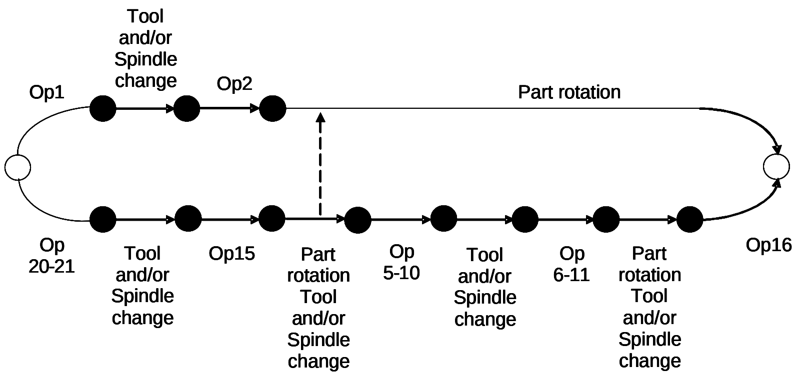


Figure 76 Step 6 for part CAI

5 Discussion

The design algorithm has successfully been applied on different parts. For part CAI more than 80 different solutions have been generated.



No of posts	1 (Part rotation module)
No of structures	2 (Parallel)
No of post changes	0
Structure 1: 2*axe, 1* tool change module (parallel to Structure 2)	
Structure 2: 1*axe, 4* tool change module, (parallel to structure 1)	

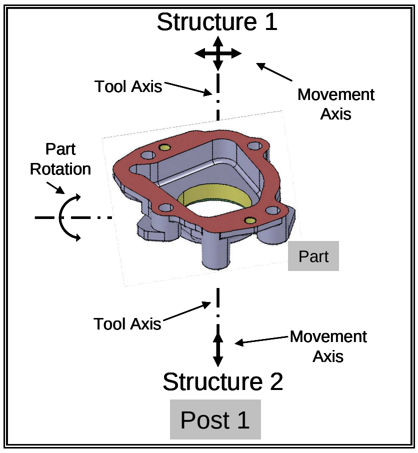
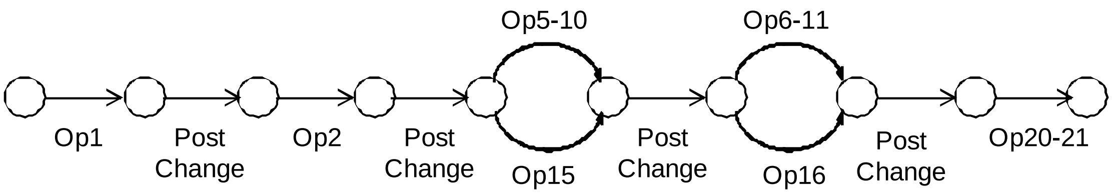


Figure 77 Graphical and schematic representation of a single post solution

They range from all machining operations on a single post to each post only having a single machining operation. The first scenario has been illustrated in the preceding section. The configuration shown in Figure 77 has two parallel structures, first as a 2-axe and other as 1-axe type. Both structures have tool change and spindle change modules. One part rotation module is also required. Figure 77 illustrates the solution in graphical form along with the schematic diagram.

However on the other extremity of the solution space another configuration of the type having only one (operations for parallel and similar features are performed simultaneously) operation is performed on each post. This type of configuration has two structures 2-axe and five structures 1axe. The important point to note is that there is no tool/broche change as well as there is no part rotation involved. This type of architectural configuration is especially suitable for high volume productions. Both the solution and it schematic diagram are shown in Figure 78 and Figure 79.



No of posts	5
No of structures	7 2 *Parallel 5 *Single
No of post changes	4
Structure 1 : 2* axe	
Structure 2 : 2* axe	
Structure 3 : 1* axe (parallel to Structure 4)	
Structure 4 : 1* axe (parallel to Structure 3)	
Structure 5 : 1* axe (parallel to Structure 6)	
Structure 6 : 1* axe (parallel to Structure 5)	
Structure 7 : 1* axe	

Figure 78: Graphical representation of five posts solutions

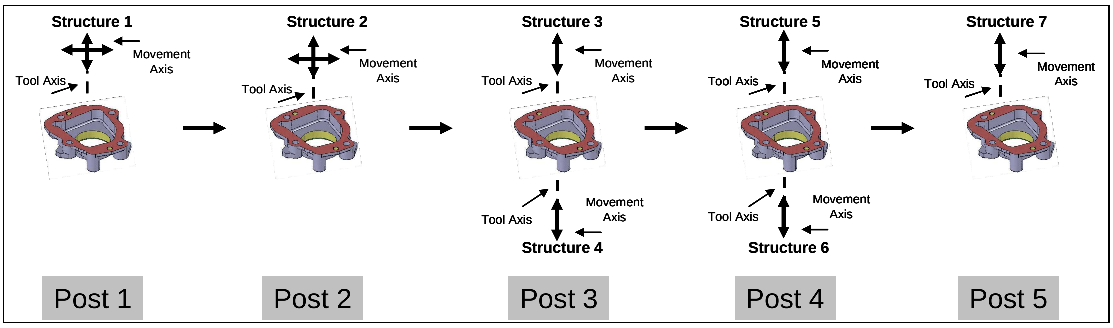


Figure 79: Schematic representation of the 5 post solution

For RMS design of the initially defined part family of the three artefacts namely; CAI, CPHC (Annex B) and CDV (Annex C), the algorithm is applied. Complete steps of the algorithm are shown in Annex D. Possible process plans for a particular set of functional requirements are generated and their corresponding architectural configurations are generated. Feasible solutions for the complete product family are selected as RMS design solutions. Optimal solution among the feasible can be found by analyzing each with respect to time and cost.

6 Conclusion

The conventional design approaches for the design of production systems are no more applicable to the recent reconfigurable systems as the criteria for the generation of process plans have been modified. The process planner no more attempts to reduce the number of part positions, rather he attempts to optimise the criteria of time and cost of machining for a work piece.

This chapter focuses on the algorithmic development of an iterative application which generates all possible process plans and corresponding kinematic structural configurations. This is achieved by instantiating different machining operations, following different intermediate criteria. The operations are grouped not only according to their accessibility direction, cutting movements but also according to possibility / impossibility of simultaneous machining.

In this chapter, an algorithmic approach is presented which iteratively explores all possible instances of configurations. Machining operations are assigned following certain criterions. Operations are not only grouped according to their accessibility, axes of movement and similarity of operations but also according to the possibility of performing the operations simultaneously. The algorithm and its implementation on a series of automobile parts have been tested so as to validate the approach.

Most importantly the algorithmic approach provides additional reconfigurabilty than conventional design of production systems. For a conventional system design approach, the particular part / part group is analysed and its machining features are identified. Subsequently for each feature its necessary machine movements are identified. After that machine selection is carried out basing on the required capability. In other words the inputs for the design of a conventional machine cell are the geometrical specifications, process plan, batch size, set of machines and machine capability. Thus the reconfigurability is at structural configuration level. However with the proposed design approach, each part has multiple pre process plans. For each of the pre process plan its precedence relationships are generated. Possible process plans and for each multiple structural configurations are generated. Reconfiguration is possible at the pre process planning stage, generation of process plans and structural configurations.

For the moment certain criterions of production system design are not taken into account. Importantly, to reduce the possible accessibility directions, a single part position on part holder is considered. A single placement is envisaged and consequently all solutions generated are for that particular part position. Secondly the generated solutions are required to be verified for absence of collisions.

These two remarks require an evaluation of the generated salutations with respect to these constraints.

Chapter 4

Approach for Evaluation of the design solutions of

Reconfigurable Manufacturing Systems

Chapter 4

Approach for Evaluation of the design solutions of Reconfigurable Manufacturing Systems

This chapter focuses on the necessity to evaluate the generated design solutions of Reconfigurable Manufacturing System. It connects and elaborates the work explained in chapter 2 regarding the definition of performance indicators as a criterion for evaluation. Evaluation criteria are defined for the generated solutions (Chapter 3) in the form of process plans and their corresponding kinematic configurations. Particular emphasis was given to the criterion of quality which is evaluated in terms of machining tolerances of the generated architectural configurations. A review of the existing techniques and methods for the tolerance evaluation is carried out. Representation of machining process plans for the proposed kinematic configurations in terms of the graphs proposed by Stephane TICHADOU and measurement of geometric deviations using one dimensional ΔL *simulation are explained and illustrated. Compatibility of the process plan / architectural configuration graphs with that of the one proposed by TICHADOU is demonstrated. Heuristics for the said graphs are defined and calculations of Internal Tolerance Condition (ITC) are carried out.* Appoaches for the 2D and 3D geometric deviation analysis are identified.

Introduction

Evaluation of the generated design solution requires certain criterions to be defined. These criterions are subdivided into static and dynamic evaluation. The static evaluation consists of the reliability, maintainability ergonomics, security… But the static evaluation is performed only after the dynamic manufacturing system architecture is chosen. For the critera linked with reconfigurability, range of product family … O.Garro proposed the dynamic evaluation criteria as productivity, flexibility and cost (Garro 1992). Flexibility includes, part mix flexibility, volume flexibility, design change flexibility…Flexibility on the time axis can be divided in three levels:

- short term flexibility is concerned with the operational level, as the dynamic affectation of one part to another machine,
- mid term flexibility is concerned with the tactical level, such as the change in the mode of realization of the parts,
- long term flexibility is concerned with the strategic level: change of production.

However flexibility at the production system level can be defined as an aggregation of all the different flexibilities. O.Garro has proposed the concept of entropy to characterize the flexibility.

Also productivity is defined as the relationship between a certain quantity of product and factors of production. (Pourcel, 1986). Cost is defined as the cost of the manufacturing activities that are performed by the manufacturing system.

The criteria for the choice of an optimal process plan are many. Among them the most important are cost (Sormaz, 03) (production, material, tooling …); time (preparation time, machining time…); machining phases; number of operations quality…These measuring criteria validates a design solution based on the measuring the difference between the desired and the actual performances, as already explained in chapter 2, where we incorporated FBS approach in the design framework. The framework acts a link between the design activities and the design solutions. This link is in the form of measureable performance indicators (PIs). These PIs serve to evaluate the design solution. Recalling the proposed framework in chapter 2, we have four basic performance measurement parameters; range of product family, quality, time and cost (Figure 80).

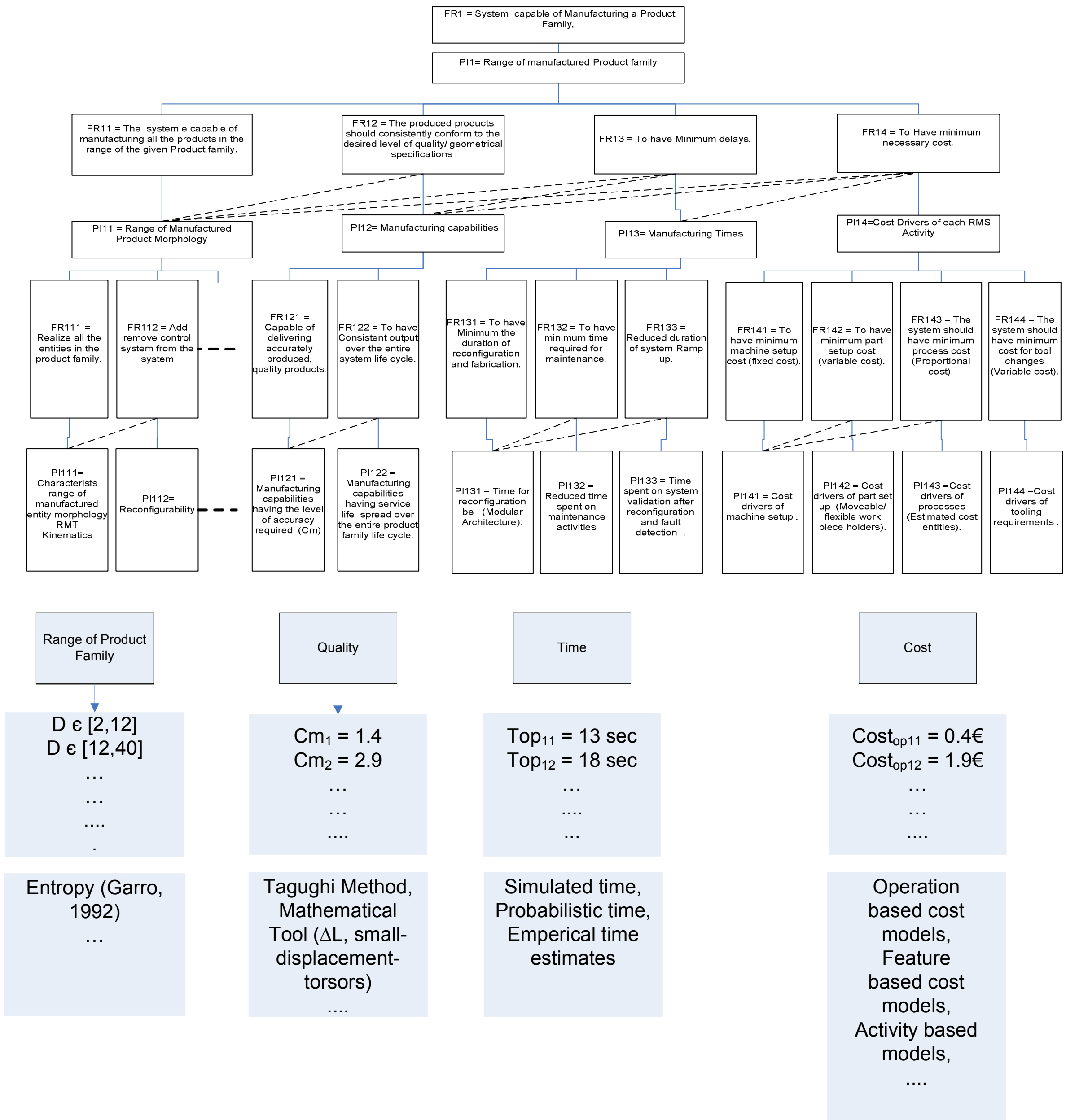


Figure 80 Performance measurement parameters

1 Evaluation

The proposed structuring in chapter 2 is based on the axiomatic design approach which has the essential objective of measuring the quality of the system in terms its aptitude for redesign and implementation. To judge the design quality, N. Suh took into consideration two axioms: the independence axiom and the information axiom. The independence axiom states that an optimal design can not be of the coupled type in passing from the required functions (independence) to the structure. An acceptable design must avoid the improvement in a function at the cost of another. The information axiom states that a design is globally optimal if it requires minimum information. Here, the information in question requires assuring the adequacy between the desired level of satisfaction of a function and the performance delivered by the system.

Following this structuring, the dependence of the four principal criteria has been identified and decomposed (Figure 80). These four indicators can be evaluated in a hierarchical manner. The evaluation approaches for these criteria are detailed in the sub sections of this chapter. Our defined PI's for the design of RMS are range of machining features in the product family, quality, time and cost. Among the four defined parameters the range of product family is the most important evaluation criterion. As illustrated in the, all subsequent parameters are affected by the choice of solution for the complete realisation of the product family.

1.1. Range of product family

The product family range represents the set of variants of machining features to be realized, the interval of the values of the feature parameters... In chapter 3, possible design solutions in the form of machining process plans and corresponding kinematic machine configurations are generated. Each solution satisfies the realization condition of the product family. These solutions explore the complete solution space for the complete manufacturing of the product family. Each of the generated design solution satisfies the first parameter of our performance domain i.e. the solution has the necessary capability to realize all machining features present in the product family. This affirmation however needs to be moderated because the constraints linked to the part positioning and collision verification are not taken into account. Therefore it is necessary to evaluate the feasibility of each generated process plan.

- The part position must be materially realisable. If the holding and clamping surfaces and not capable of maintaining the part position, then the process plan and the kinematic configurations are not capable.
- Collisions must be detected. In his PhD thesis H. Aladad (Aladad, 2009), used the software DELMIA so as to validate the kinematic s of a reconfigurable machine tool.

1.2. Quality

The second most important performance evaluation aspect is the quality of the realized product family i.e. depending on the choice of kinematic solution the quality will vary. Quality represents the guarantee to the product conformity. If the geometric error of the part realized on one of the generated solution is more than the desired tolerance, the process plan and the kinematic configurations are not capable. The manufactured machining features should have a geometric and dimensional quality within the defined tolerance limits.

From an industrial view point the study and analysis of machining tolerances with respect to quality is very important. The evaluation of this criteria attempt forecast the probable behaviour of the production system following process plan via the simulations. These simulations allow taking into account the cumulative effect of these manufacturing deviations. Also this approach has not yet been integrated in the process plan generation system (Tichadou, 2005). To do this it is necessary to study the possible sources of machining errors, their contribution towards quality and their effect on the functional aspects of the product. This requires definition of the dimensional specifications between active surfaces during a machining phase called “cotation de fabrication” and simulation of the machining operations to analyse the effect of the operations on these dimensional specifications on the active surfaces of the work piece (surfaces which are machined or are used during the part positioning).

The manufacturing specification consists of determining the specification of the part in its intermediate state; it quantifies and defines the type of associated tolerance. P. Bourdet (Bourdet 73a, Bourdet 73b) stated that each active surface in a phase evolve, in a limited area and limited space of the machine. The dispersal area, called Δl, is attributed either to machining errors or setting errors. The tolerance intervals for a given manufacturing specification in a machining phase (Figure 81), between two surfaces I and j is given by the formula: ITCfij = Δli + Δlj.

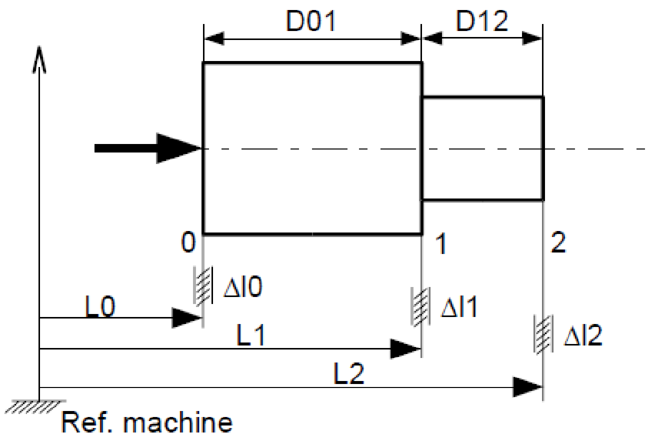


Figure 81 One dimensional modelling of a machining phase (Bourdet 73a)

Machining phases can be represented graphically. It is an effective tool to generate datum chains. Mainly there are two methods for graphical representation in one dimensional tolerance analysis, the method “digraphic” proposed by P.Ji (Ji, 99) and “exploitation graphique du tableau des Δl” proposed by P.Bourdet.

There number of works regarding the 3D simulation of machining is very less (Tichadeau, 2005). Spiewak (Spiewak, 94) propose the kinematic and geometric simulation of a machining phase of milling operation. But this study was limited to a single phase and succession of phases cannot be integrated. The kinematic modeling of manufacturing errors proposed by Bénéat (Bénéat, 2001) allows to simulate the manufacturing of a part. The modeling is based on the representation of machining errors by jacobian matrices. Uncertainty tensor was proposed by Clément (Clément, 1996). This method permits to analyze the dispersion due to part setup but does not take into account the errors due to machining. Modeling of the geometric deformation and deviations by small displacement torsors is proposed by Villeneuve and Legoff (Villneuve, 2001). Stephane Tichadou (Tichadou, 2005) also modeled the geometric deviations using small displacement torsors. He graphically represented the process plans and kinematic machine configurations. The process plan graphs used by Tichadou are important tools to illustrate the relations between different elements of the kinematic chain. In conclusion there are studies in the case of one, two or three dimensional quality. The different approaches of machining simulation (one or three dimensional) use the geometric deviation models.

1.3. Cost and Time

Cost represents the expenses incurred for the production of a product. The time represents the duration of each operation or activity (production activity, preparation activity, reconfiguration activity ...)

Manufacturing cost and time estimations are can be performed by different approaches: parametric, analytical and analogical.

The analogical methods are based on evaluation of the cost of a new product with that of an existing one. The cost of the existing one is described with the help of parameters judged discriminating and pertinent (like morphology, quality, dimensions ...) which allow also describing the new product for which the cost estimation is being done. This approach is similar to the variant process plan generation approach.

The parametric cost estimation methods include the methods which are based on the knowledge of the mathematical relations linking them to quantifiable parameters of the product such as volume, time etc.

In the analytical methods we group all the methods that take into account necessary sequenced operations and activities with associated kinematic modules. Thus we have retained the approach “Activity Based Costing (ABC)” (Park, 1995; Ioannou, 1999, Ong, 1993).

After the identification of the activities and resources (kinematic modules) is done, ABC method quantifies three inductors to calculate the cost:

- Resource inductor: allows distributing of the resources between activities. This allocation can be: time allotted to each activity, or the quantity of raw material.
- Cost inductors: It is the factor influencing the performance level of the activity and its consumption of the associated resources.
- Activity Inductor: This inductor allocates the costs of activities between different products.

$$Coût = \sum_i (Ind_i^A .\ Ind_i^C .\ Ind_{i,j}^R .Cout_j)$$

Ind_i^A : Inductor of activity $_i$

Ind_i^C : Inductor of cost of activity $_i$

$Ind_{i,j}^R$: Inductor of resource linking an activity $_i$ to the resource $_j$

$Cout_j$: cost of the resource $_j$

All these inductors can be identified for each arc of the graph of the generated solutions.

Cost estimation based on ABC can adopted to form the basis for estimating cost and time as proposed by Feng (Feng, 2000). Each manufacturing activity can be one of many processing activities, such as setup, load/unload, handling, processing, and idling. Each processing activity involves cost of using any resources and overhead cost. Cost and time estimating equations are described in the following equations by Feng:

1.3.1 Manufacturing cost estimatiion

where

$$C_m = \sum_{i=1}^{N} C^i_{activity}$$

$$= \sum_{i=1}^{N} \left(C^i_{processing} + C^i_{setup} + C^i_{handling} + C^i_{load-unload} + C^i_{idling} + C^i_{overhead} \right)$$

C_m	is manufacturing cost of an artifact.
i	is an index.
N	is the total number of manufacturing activities applied to manufacture an artifact.
$C^i_{activity}$	is the manufacturing cost of activity i.
$C^i_{processing}$	is processing cost of activity i.
C^i_{setup}	is setup cost of activity i.
$C^i_{handling}$	is handling cost of activity i.
$C^i_{load\text{-}unload}$	is load and unload cost of activity i.
C^i_{idling}	is idling cost of activity i.
$C^i_{overhead}$	is overhead cost of activity i.

I - Processing cost

$$C^i_{\text{processing}} = C^i_{equipment} + C^i_{labor} + C^i_{material} + C^i_{tool}$$

$C^i_{equipment}$	is the equipment cost of activity i. Equipment cost is decided by the time the equipment being used and the cost per unit time.
C^i_{labor}	is the labor cost of activity i.
$C^i_{material}$	is the material cost of activity i.
C^i_{tool}	is the tool cost of activity i.

II - Tooling activity cost

$$C^i_{tool} = C^i_{fixture} + C^i_{cuttingTool} + C^i_{gaugeTool} + C^i_{accessoryTool}$$

$C^i_{fixture}$	is the fixture cost of activity i
$C^i_{cuttingTool}$	is the cutting tool cost of activity i
$C^i_{gaugeTool}$	is the gauging tool cost of activity i
$C^i_{accessoryTool}$	is the accessory tool cost of activity i

III - Setup activity cost

$$C^i_{setup} = C^i_{s-machine} + C^i_{s-tool} + C^i_{s-workpiece}$$

$C^i_{s\text{-}machine}$	is the machine setup cost of activity i.
$C^i_{s\text{-}tool}$	is the tool setup cost of activity i.
$C^i_{s\text{-}work\ piece}$	is the work piece setup cost of activity i.

Tool cost is decided by the time the tool being used and the cost per unit time.

In our case of cost estimation for a technological aspect of the design solution of RMS, $C^i_{processing}$ is the machining cost. As the part is fixed only once for all configurations so we have a fixed C^i_{setup} for all solutions.

1.3.2 Manufacturing time estimation

$$t_m = \sum_{i=1}^{N} t^i_{activity}$$

$$= \sum_{i=1}^{N} \left(t^i_{processing} + t^i_{setup} + t^i_{handling} + t^i_{load-unload} + t^i_{idling} \right)$$

t_m is the estimated manufacturing time of an artifact.
i is an index.
N is the total number of manufacturing process of an artifact.
$t^i_{processing}$ is the processing time of activity i.
t^i_{setup} is the setup time of activity i.
$t^i_{handling}$ is the handling time of activity i.
t^i_{load} is the load and unload time of activity i.
t^i_{idling} is idling time of activity i.

$$t^i_{setup} = t^i_{s-machine} + t^i_{s-tool} + t^i_{s-workpiece}$$

$t^i_{s\text{-}machine}$ is the machine setup time of activity i.
$t^i_{s\text{-}tool}$ is the tool setup time of activity i.
$t^i_{s\text{-}workpiece}$ is the workpiece setup time of activity i.

1.3.3 Relationship with graphical solutions

In our case of RMS design, the design solutions are represented in graphical form as presented in chapter 3. They are a ordered set of machining operations along with different part / tool / spindle movements (Figure 82). Each operation and movements incurs certain cost and time.

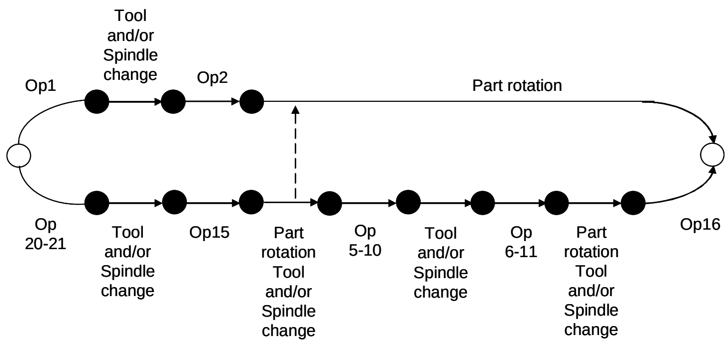


Figure 82 Graphical solution

The manufacturing cost Cm of the part is the sum of the cost of all the activities involved in the manufacturing process. There are 12 manufacturing activities "N". The activities include machining operations and tool /spindle/ part rotation. {Op1, Op20, Op21, Op2, Op15, Op5, Op10, Op6, Op11 and Op16} are the machining operations incurring Ciprocessing . This processing cost includes material tool and labour costs for the above mentioned machining activities. For our RMS design solutions we have only one Cisetup.. For the moment we have not considered Ciidling, and Cioverhead . Also there is no Ciload-unload. Simiarly time estimation tm can be carried out for the generated solutions. The times; tiprocessing , tisetup and tiload can be calculated similarly as that for cost.

A product, in its manufacturing phase can be divided in five levels form geometrical point of view. They are before project, product, part, part under manufacturing and finally the part surface. The associated competences to these levels are globally design, industrialization and production. Each level is oriented towards the common objective i.e. to have a product having geometrical characteristics closest to the nominal one.

In this chapter, we have focused towards the evaluation of geometrical and dimensional characteristics of the kinematic chain of the manufacturing system by geometric simulation of the machining processes. Each configuration has a particular set of geometrical characteristics, associated to it and will affect the final product realized. Thus, there is a need to have a method to validate the proposed configuration so that it is apt to guarantee the conformance of the work piece.

2 Geometric simulation of the machining processes

In this section, we focused on assessing the geometric and dimensional characteristics of the kinematic chain of the manufacturing system. Each configuration has a particular set of geometric characteristics. Thus, we need a method to validate the proposed configurations.

The approach allowing to mathematical formalization of the specifications and uncertainties of manufacturing process, and to express the expected geometric behavior, is the Δl approach developed by P. Bourdet (Bourdet 1975). This approach proposes to quantify the manufacturing dimensioning (cf) from the functional dimensions (FC), regarded as known. This approach consists of two major steps:

- The first is to establish a simulation graph which is a modeling of the machining process. In this model, each surface is represented by a column, and each coordinate correspond to a step in the manufacturing process. The crosses designate the created surfaces and triangles represent the surfaces participating the positioning of the part. The tolerance intervals of the dimensional simulation are noted as Δli for the created surfaces and Δlij to contact surfaces. The index i is the number of the concerned surfaces, the exponent j is the number of phase or coordinate.

- From this graph, the approach proposes to establish formal relations between the produced dimensions (and their associated tolerance intervals Δli) for each functional dimension. Since the approach is based on a one-dimensional modeling, the minimum pass is unique. Writing these relations is thus quick and unequivocal. These relationships help to validate the spectrum of machining process plan.

This approach has been generalized by S. Tichadou who proposed the use of graphs to formalize the dimensioning of machining process plan and the use of small displacement torsors model these defects / deviation. This approach is based on modeling the manufacturing process, highlighting the main relations of (contact, machining and positioning) between geometric entities of the part and machining resources (machine, part holder and l 'machining operation used). This model then allows the identification of play and error that are required to be formalized in the form of torsors.

Given some similarities between the graphs developed by S. Tichadou and our graphs proposed in Chapter 3, we chose to adapt his approach to our problem. In his thesis research Tichadou proposed the use of graphs to illustrate the process plan and use of small displacement torsors to model the tolerances.The proposed method interests us due to its proximity with our objective i.e. simulation and measurement of geometric deformation. Also the graphical representation of the machining process plans is very similar to our generated graphical solutions. We attempt to demonstrate the compatibility of the method proposed by Tichadou to be used for evaluation of the generated design solutions (Chapter 3), with respect to manufacturing tolerances and quality.

In the modelling technique under discussion, the process plans are a succession of machining phases. To find the sources of the geometrical deviations in the manufacturing process, it is pertinent to model a machining phase after having listed all the elements and potential errors of machining. A process plan is described by representing as a graph. With theses graphs, it will be possible to visualize the sources of deviations that are originated due to positioning errors with respect to the machining surfaces of the part.

The machining simulations are to be carried out with an objective of forecasting the geometric deviations of the features during and at the end of the machining process. These deviations are the geometrical and dimensional variations, appearing during the machining phases. The modelling by Tichadou is based on the concept of elementary machining cell or a machining post. A machining cell or post is composed of its following main constituent elements.

- Machine Tool: It is a set of electro-mechanical equipment, composed of multiple liaisons directed and controlled to generate the relative cutting movements between the part and the tool.
- Part holder: it has the principal function of positioning and holding the part
- Part to be machined: It’s a solid, which can be in its original or intermediate state during a machining process.
- Tools and their attachments: Assembly of different components (tool holder, featuring elements, start and stop of cutting motions…).
- Work trajectories: relative movements between the tool and the part describing the kinematic machining conditions.

In our case the elementary machining cell includes the following elements:

- Post (Chapter 3)
- Structure similar to the machine-tool: a set composed of several liaisons driven and controlled to generate relative movements of cutting and advance between the part and tool; a post can have multiple structures performing operations simultaneously.

- Part Holder: mobile assembly moving from post to post whose main functions is to position and hold the part during machining operations performed by the structures.
- Part to be machined: solid from the previous position in an intermediate state.
- tools and their attachments: assembly of different components (cutting edge, insert holder, tool holder, clamping elements, etc.).
- Working trajectories: relative motion between tool and part describing the kinematic machining conditions.

2.1. Sources of manufacturing deviations

An error is defined as a domain between the desired nominal situation and the actual or real situation. A manufacturing error causes geometrical and/or dimensional deviations on the part to be manufactured. The manufacturing errors originate from the intervening elements during each machining phase.

Machining errors have two origins: either, it is linked to the errors of the intrinsic characteristics of each machining feature, or, they are the function of coupling between multiple features. In other words, if the dimensions and the geometry of machining features are different from the desired one or the positioning between each feature is disturbed, errors and deviations are expected to be present on the part.

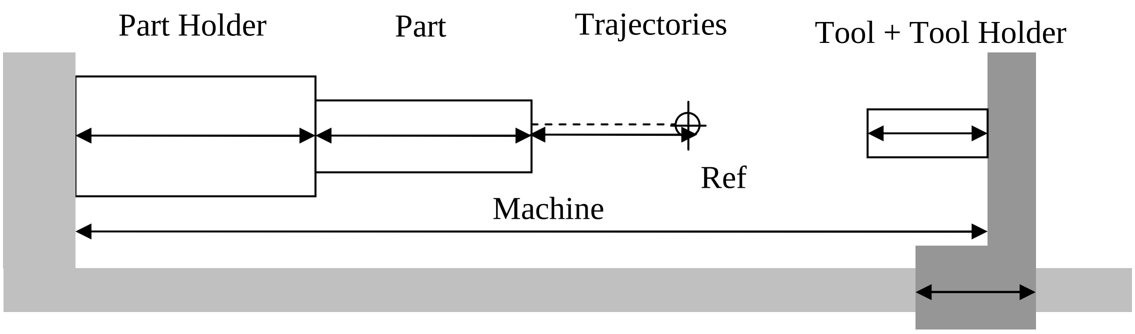


Figure 83 Errors generated by dimensioning errors of entities

The errors pertaining to the intrinsic characteristics of machining features are given below along with their related machine elements (Figure 83):

- Machine tool: The structural deviations of the liaisons of moving elements, non circular rounds, geometric deviation of solids, thermal expansion, machine deformation… The non continuous behaviour due to the usage conditions (high speed and mechanical actions). Dimensional specification (Cf) (Dugus, 2002) for the prediction of deviation due to dynamic behaviour.
- Part Holder and Tools: Geometrical deviations, measurement errors and deformation generated due to the mechanical actions of machining. Dimensional specification (Li, 99) for the modelling of deformation of part holder and (Seo, 1998) (Larue 2003) for the simulation of the tool deflection.

- Part or feature in its intermediate state: The correctness of dimensions of a part in its intermediate state, due to either the precedent phase or precedent operation (Raghu, 2004).
- Calculation errors machine trajectory
- Positioning errors: They include:
  - the part and the part holder (Rong, 2001)
  - the machine and the part holder (Armillotta, 2001), (Musa, 2004a)
  - the machine and machining trajectories (localisation errors)
  - the machine and tool

Our work focuses on the determination of the geometric and dimensional deviations of kinematic chains for the manufacturing of a group of parts. These deviations are considered to be generated during machining operations. In our case, we can add the following sources:

- On the part holder: positioning defects of the part holder on the post and rotation of the whole part and part holder set.
- On the structure: the deviations cited above for the machine tool plus the reconfiguration defects of the structure on the post.

2.2. Machining phase modelling

Tichadou proposed to perform the simulation of a machining process (in phases). For this, four physical elements are taken into consideration. They are the part to be manufactured P, the part holder H and the machine tool MT. A new supplementary physical component, machining operation Mm (Tichadou, 2005), has been created.

The machining operation is seen as a virtual solid described by the trajectories of the machining tool and tool post on the work piece in the machine space. The machining operation is a function of the trajectories, the kinematic structures of the machine tool and the tool used.

In the modeling approach the surfaces in a phase for each machining phase were identified:

- The surfaces Pi1 of the work piece P. They include the positioning surfaces and the machined surfaces that result from the tooling during a machining operation Mm2. These surfaces are called the active surfaces.
- The part holder surfaces, that are at the interface of the part and the part holder and contact surfaces between the part holder H and the machine tool MT.
- The machining surfaces Mml3 generated by tools during one of the machining operations Mm while realizing the surfaces Pi of the work piece P.

---

[1] Pi : Surface “i” of the part

[2] Mm : Machining operation « m » of the phase

[3] Machining Surface « l » of the machining operation Mm

To adapt this graph to model a machining process plan performed on a RMS, several concepts have been modified:

- The notion of phase has been replaced by the notion of post.
- The fact that it is possible to have multiple structures on a single post has been modeled by several machines in the same phase,
- The fact that it is possible to rotate the part on post and thus realize more features using the same structure was modeled by duplicating the phase and by incorporating an element “position "

3 Graphical representation of a machining phase

Multiple studies have shown interest to represent the relations between surfaces of the part by using graphs (Ballu, 1999), (Case, 1999). A graph represents a series of binary relations between the elements. Different graphical representations of a machining phase have been proposed. They include the representation of one dimensional cases (Ji 1999) and two dimensional cases (Xue, 2002). A three dimensional modeling graph was proposed Bénéat (Bénéat, 2001), but it differentiated the sources of different types of deviations in the representation.

A detailed description of the graphs used by S. Tichadau in his approach for the three dimensional modeling of a machining phase is given in the subsequent sub sections. It starts by finding out the elements that participate in the machining phase. The basic components are work piece or part, part holder, the machine tool and the machining operations. The data is homogenized in the form of solids and surfaces. Considering the machining operations as virtual solids, permits the integration of all errors relative to tools, machining and trajectories.

The graph is a support to three dimensional simulation of machining deviation and it gives us:

- lists all the surfaces and solids in a machining phase,
- places the geometrical deviation between different elements,
- represents phase by phase graph which permits a local analysis
- Illustrates the geometrical deviations with out associating them to any particular typology.

The graphs proposed in the methodology contain blocks and links. The physical elements are defined by the rectangular blocks and the binary relations between these elements by the links as shown in Figure 84. The solids and surfaces are differentiated by a slightly curved corner block.

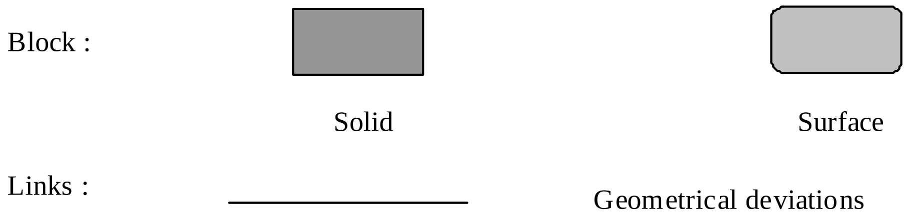


Figure 84 Elements of the graph

In this graph the rectangular blocks are:

- The theoretical model of the part P and its active surfaces. They include the positioning surfaces (P1, P2, and P3) as well as the machining surfaces (P4, P5, and P6).
- The part holder (H) and its surfaces. They include contact surfaces with the work piece (H1, H2 and H3) and with the machine (H1-1, H2-1 and H3-1).
- The machine tool (MT) and its contact surfaces with the part holder (MT1, MT2 and MT3).
- The machining operations (M1 and M2) and their machining surfaces (M11, M12 and M21).

Geometrical deviation exists between each of these elements, thus there will be links between these elements. Figure 85 shows the liaisons inside a machining element and also between the elements for a machine tool "MT" having part holder H, for part "P" having surfaces (P1, P2… P6). The part P is manufactured through machining operations M1 and M2 having M11, M12 and M21 as their machining surfaces.

In the approach under consideration, the whole process plan is represented with the help of a set of graphs, each representing a phase. The associations of graphs to each machining phase describes the process plan following the proposed modeling approach and also allows to identify the origins of positioning errors relative to part surfaces as a function of machining processes. This graphical technique is also applicable to represent one, two or three dimensional modeling of geometric deviations during the machining processes.

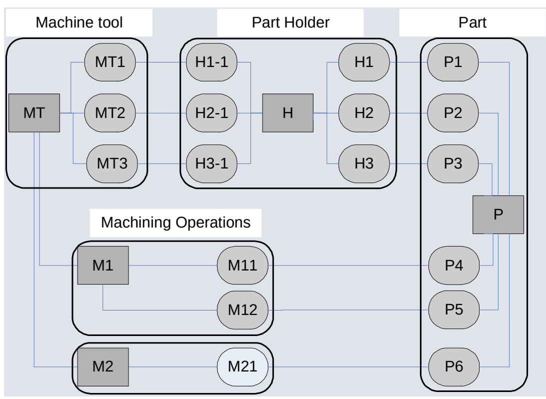


Figure 85 Graphical representation of a machining phase with reference to geometrical deviations

The methods permitting a representation of the deviation between components include homogeneous transformation matrix and small displacement torsors. Utilization of small displacement torsors is more favored in contrast to complex matrix calculations for the movement of coordinates; it allows a mathematical formulation based on linear algebra. In the next sub section, the typology of the torsors and their use in modeling of a machining process plan is explained.

3.1. Representation of deviation with a small displacement torsor

The torsor presented by P. Bourdet et A and A. Clément (Bourdet, 1988), represent the displacement between two entities E1 and E2 as two vectors $\vec{\Omega}$ and $\vec{Do}$. In a base B ($\vec{x}$, $\vec{y}$, $\vec{z}$), the vectors are expressed as:

$\vec{\Omega} = \alpha.\vec{x} + \beta.\vec{y} + \gamma.\vec{z}$ where α, β, γ are the three small angles of linear rotation.

$\vec{Do} = u.\vec{x} + v.\vec{y} + w.\vec{z}$ where u, v, w are the three projections of the translations.

Torsor $T_{E1,E2}$ is expressed as:

$$\text{Notation : } \mathbf{T}_{E1,E2} = \begin{Bmatrix} \vec{\Omega} \\ \vec{D_O} \end{Bmatrix}_O = \begin{Bmatrix} \alpha & u \\ \beta & v \\ \gamma & w \end{Bmatrix}_{O,B}$$

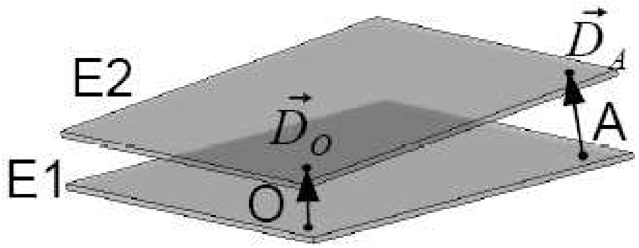


Figure 86 Equi-projection of the translation

3.2. Typology of the torsors used in machining simulation

Four types of deviations in a machining process plan are modeled with help of small displacement torsors i.e. error torsor, deviation torsor, play or connection torsor and global torsor. The error torsor represents the displacement between a theoretical nominal surface and the position of the real surface. These torsors only depend on the topology of the surface. A deviation torsor represents the deviation of difference in position between two surfaces of the same work piece. The connection or play torsor represents the positioning error between two surfaces of two solids. The global torsor represents the deviations of position of a solid with respect its nominal position

The geometric deviations between the elements in a machining phase are associated with a particular small displacement torsor. Global toror is used to give deviations in machine tool and tool positions. Play or connection torsor represents contact error between part holder and part surfaces and also between machining operations and machined surfaces. Finally error torsor represents the dimensional errors of machined surfaces.

A geometrical machining condition is a constraint that links two surfaces of the machined part. To simulate the geometrical behavior, it is sufficient to add the set of different torsors present in the component loop (Thiebault, 2001). With the help of graphical representation of the machining phases, the expression of this condition will be the sum of different small displacement torsors which are present in the machine element chain linking the two surfaces. An example of the geometric condition in the form of a torsor chain is given in Figure 87.

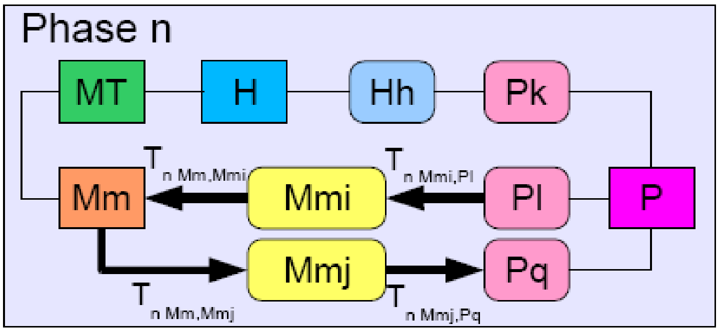


Figure 87 Torsor chain of a graph representing phase n

It determines the geometric deviation between two surfaces, Pl and Pq, machined with the same tool in the same phase n. The closed loop of the torsor chain is written as:

$$T_{Pl,Pq} = - T_{n\ Mmi,Pl} - T_{n\ Mm,Mmi} + T_{n\ Mm,Mmj} + T_{n\ Mmj,Pq}$$

This formalism models up to three dimensional geometrical deviations between two machined surfaces in one single equation. It requires writing of constituent torsor equations and then the closed loop torsor chains. These two activities are distinct and will be executed separately.

As a function of the type of conditions between two surfaces, there can be multiple chains linking the surfaces. For a multi phase process plan these chains can pass from one phase graph to another. These conditions can be between two machining surfaces, one machining surface and one positioning surface or between two surfaces realized in different phases.

The representation of the geometric condition between two surfaces with the help of a torsor chain becomes our point of interest. This representation will help in carrying out a one, two or three dimensional analysis of the generated process plans and structures.

With reference to our objective of analysis and evaluation of the generated structures, the modeling approach for simulation of geometric deformations is applied with certain modifications as discussed earlier. These changes have necessitated the addition of heuristics in the processing of these graphs (computing dimensional chains):

- If structure i appears 2 times in the chain then the second occurrence is not taken into account in the accumulation of defects
- If spindle i appears 2 times in the string chain the second occurrence is not taken into account in the accumulation of defects
- If the element "position" appears only once in the chain then this case is not taken into account when the total defects.

As for the moment, the proposed RMS design requires a single positioning of the part on the part holder and this remains the same though out the process plan, so the geometric deviation between machine tool – part holder and part holder – part are neglected. However, new geometric deviations between machine tool, post, part positions and structures are added.

A generic view of the graphical representation of the generated RMS process plan and kinematic configurations is shown in Figure 88. Following an adaptation, it is possible to visualize the procedure of "mapping" of the graphs of the generated solution in chapter 3. This mapping is simple due to the similarity of the manipulated concepts.

- Post ≈ Post,
- Operation ≈ Surface + Operation + spindle,
- Part rotation ≈ Position,
- Set of operations in series on a post ≈ Structure

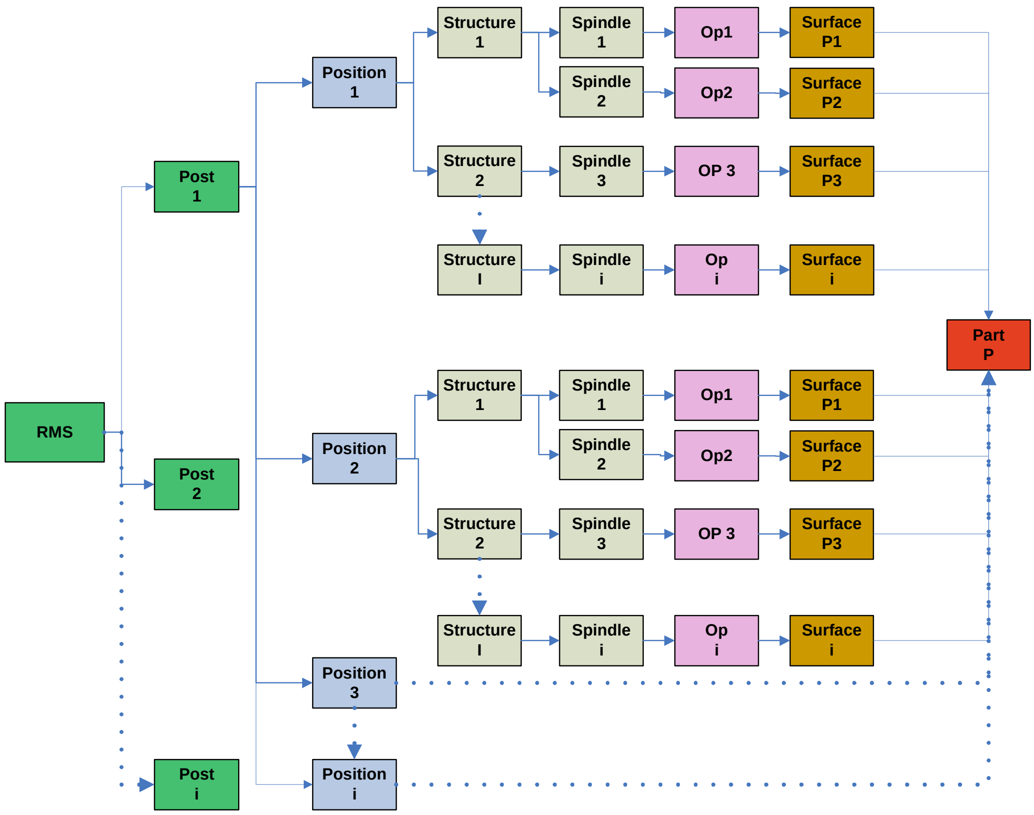


Figure 88 Graphical representation model for a generated solution of RMS

4 One dimensional analysis based on ΔL

From the graphs, an approach to one dimensional or three-dimensional machining simulation is possible, based on modeling of geometric imperfections by Δl or torsors of small displacement. Returning to the compacted graph representation; we can list the types of Δl or torsors that characterize geometric deviation “because" or "between" the different elements: Δl Operation, Δl spindle + tool, Δl Structure, Δl position, and Δl Post.

For the analysis, we have used the following values of associated error / deviation with respect to different activities related to tool, spindle, structure, position and part change activities in part manufacturing process (Table 4). This data is based on the input by experienced operators. Also, ΔL associated to the machining operations and machining surfaces is called ΔL-Tool.

Values for ΔL (mm)	
ΔL tool	0.002
ΔL Spindle	0.004
ΔL Structure	0.003
ΔL Position	0.004
ΔL Post	0.006

Table 4 Values of Δl

Each specification constrains geometric defects of position or orientation relative between two surfaces of the part. Using graph representation, the expression of each resulting Δl associated to each specification is the sum of Δl located on the path between the two surfaces. It is sufficient to simply write each closed chain to find the different components of Δl to formulate the condition:

IT specif $\geq$ Δl resultant = $\sum \Delta l \in \text{Chain}$

4.1. Application for the design on RMS

The generated process plans and their corresponding structures are represented as graphs and one dimensional tolerance analysis is carried out. We have chosen two solutions (generated and illustrated in Chapter 3) that represent the extremities of the solution space. The first solution has all the machining operations performed at a single post. It has a no of tool and/or spindle change and/or part rotation activities. The other has the machining activities spread out on numerous posts. It has a number of part rotation or tool/spindle change activities and resembles a dedicated manufacturing line.

To illustrate the generation of the graphical representations, we continue the use of part CAI. All machining features required to be realized along with the operations to be performed are shown in Figure 89. The functional diagram showing all the liaisons between different surfaces for part CAI is given in Annex E. The graphs are modeled as a RMS having one or multiple posts, for each post there can be different positions of the work piece. Further, at each position one of more structures are present to perform machining operations. Each structure can have single or multiple spindles performing machining operations “OP” on part surfaces “P”. Here the rough and finishing operations for the same machining feature are considered as two independent operations and are scheduled independently.

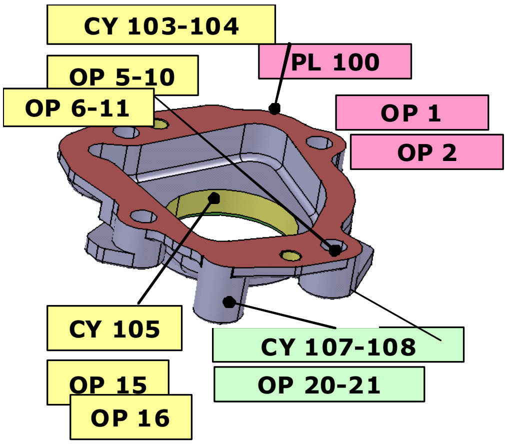


Figure 89 Part CAI

4.2. Solution having a single post

The corresponding structure for the above part in Figure 89 along with its corresponding process plan is given in Figure 90.

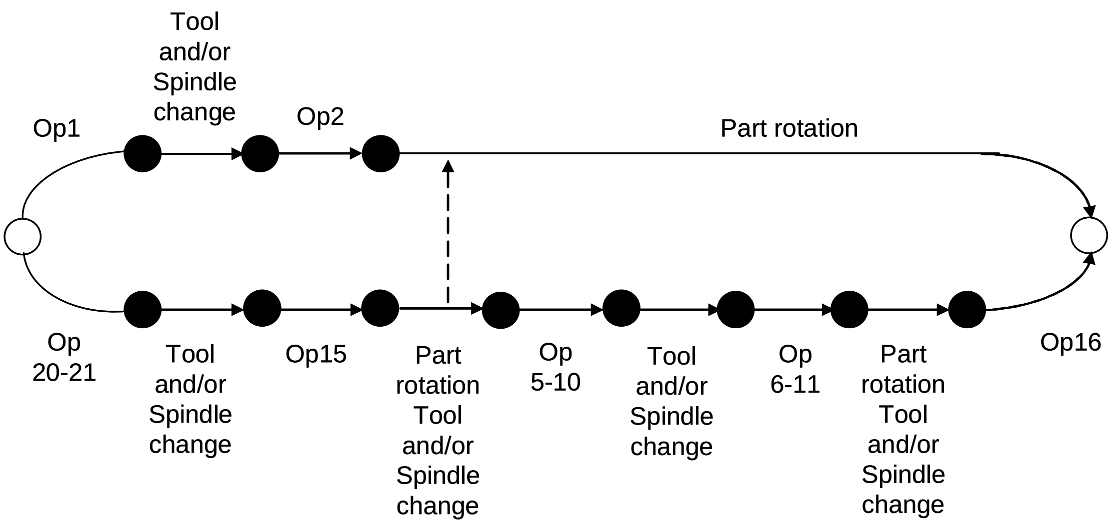


Figure 90 Single post generated solution

The shown kinematic configuration is based on all the machining operations performed on a single post. Thus there is no post changing activity and consequently no deviation associated to it. It has two parallel structures each having multiple tool and/or spindle and/or part rotation activities. The configuration can be graphically represented as below (Figure 91):

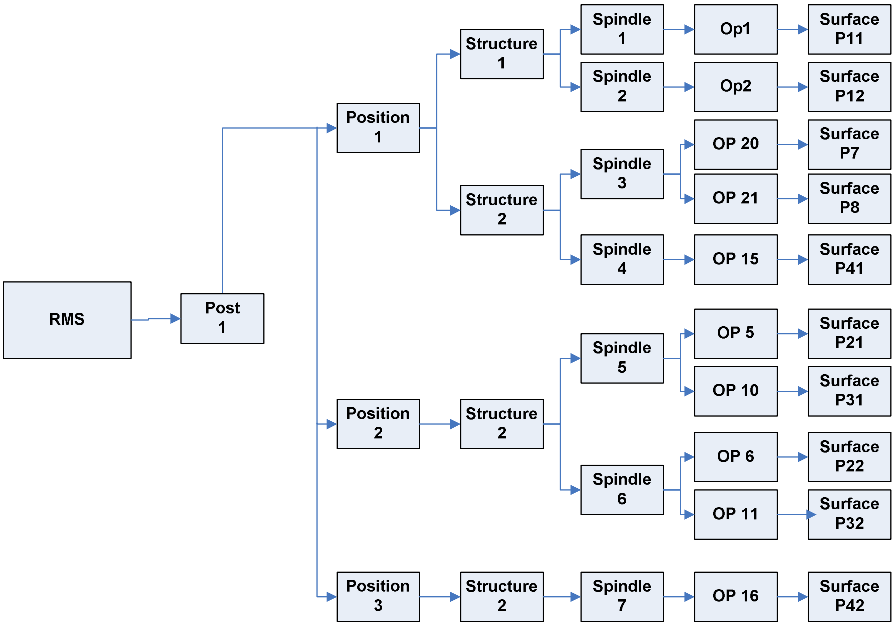


Figure 91 Graphical representation of a single post solution

There are 11 liaisons between realized surfaces as given in the functional drawings (Figure 92). Each liaison is in the form of a chain of interacting elements.

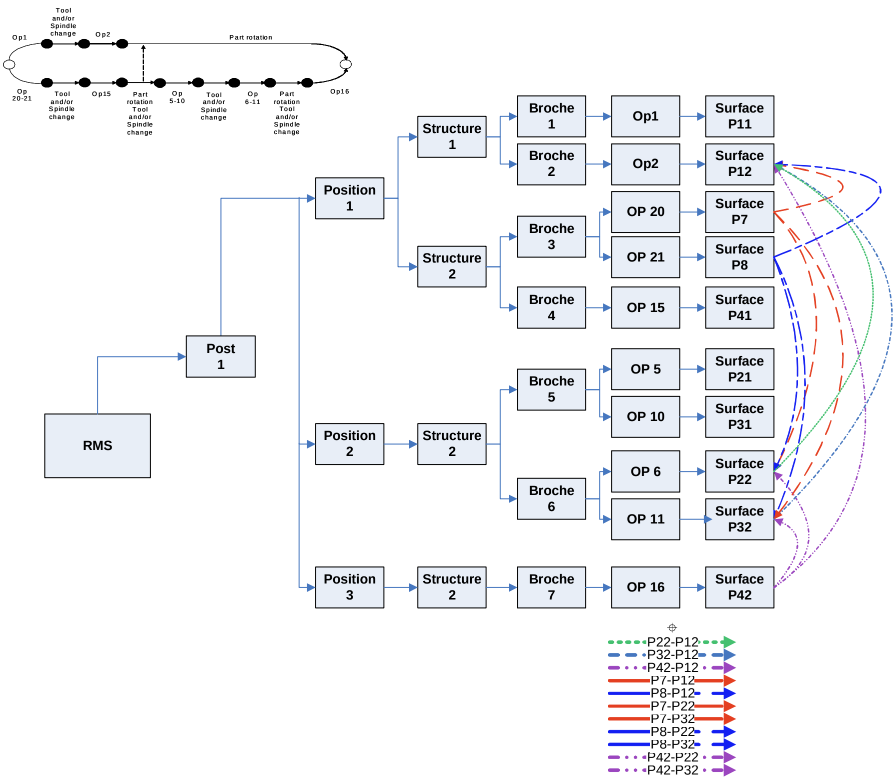


Figure 92 Possible liaisons between interacting surfaces for single post solution

Using the defined heuristics for the graphs, calculation of Internal Tolerance Condition (ITC) is done as follows:

$ITC_{P22\text{-}P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Structure2} + \Delta L_{Broche6} + \Delta L_{Tooling22}$

$= 0.002 + 0.003+ 0.004 +0.004 + 0.004 +0.004 + 0.003 +0.002$

$= 0.026$

$ITC_{P32\text{-}P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Structure2} + \Delta L_{Broche6} + \Delta L_{Tooling32}$

$= 0.026$

$ITC_{P42\text{-}P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + \Delta L_{Position\ 1} + \Delta L_{Position\ 3} + \Delta L_{Structure2} + \Delta L_{Broche7} + \Delta L_{Tooling42}$

$= 0.026$

$ITC_{P7\text{-}P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + + \Delta L_{Structure2} + \Delta L_{Broche3} + \Delta L_{Tooling7}$

$= 0.018$

$ITC_{P8\text{-}P12} = \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure1} + + \Delta L_{Structure2} + \Delta L_{Broche3} + \Delta L_{Tooling8}$

$= 0.018$

$ITC_{P7\text{-}P22} = \Delta L_{Tooling7} + \Delta L_{Broche3} + \Delta L_{Structure2} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Broche6} + \Delta L_{Tooling22}$

$=0.022$

$ITC_{P7\text{-}P32} = \Delta L_{Tooling7} + \Delta L_{Broche3} + \Delta L_{Structure2} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Broche6} + \Delta L_{Tooling32}$

$= 0.022$

$ITC_{P8\text{-}P22} = \Delta L_{Tooling8} + \Delta L_{Broche3} + \Delta L_{Structure2} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Broche6} + \Delta L_{Tooling22}$

$= 0.022$

$ITC_{P8\text{-}P32} = \Delta L_{Tooling8} + \Delta L_{Broche3} + \Delta L_{Structure2} + \Delta L_{Position\ 1} + \Delta L_{Position\ 2} + \Delta L_{Broche6} + \Delta L_{Tooling32}$

$= 0.022$

$ITC_{P42\text{-}P22} = \Delta L_{Tooling42} + \Delta L_{Broche7} + \Delta L_{Structure2} + \Delta L_{Position\ 3} + \Delta L_{Position\ 2} + + \Delta L_{Broche6} + \Delta L_{Tooling22}$

$= 0.022$

$$ITC_{P42\text{-}P32} = \Delta L_{\ Tooling12} + \Delta L_{\ Broche7} + \Delta L_{\ Structure2} + \Delta L_{\ Position\ 3} + \Delta L_{\ Position\ 2} + + \Delta L_{\ Broche6} + \Delta L_{\ Tooling32}$$

$$= 0.022$$

4.3. Solution having a five posts

The corresponding structure for this process plan and its structural configuration is given in Figure 93.

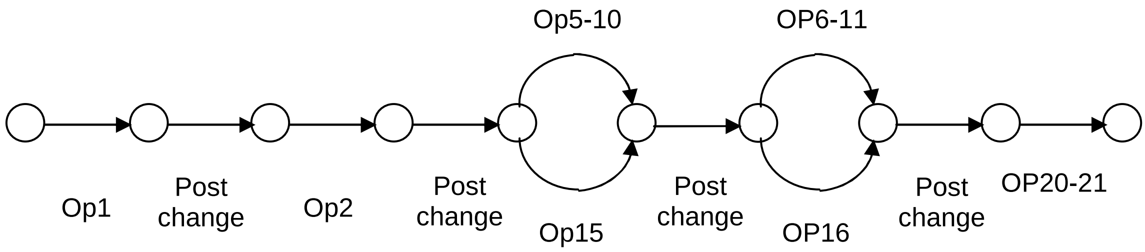


Figure 93 Five posts generated solution

The shown kinematic configuration is based on each of the machining operations performed on a single post. Thus there is no tool change or spindle change activity and consequently no deviation associated to it. It has five posts and two parallel structures along with four post change activities. The configuration can be graphically represented as below (Figure 94):

Figure 94 Graphical representation of a multi post solution

There are 11 liaisons between realized surfaces as given in the functional drawings (Figure 95). Each liaison is in the form of a chain of interacting elements.

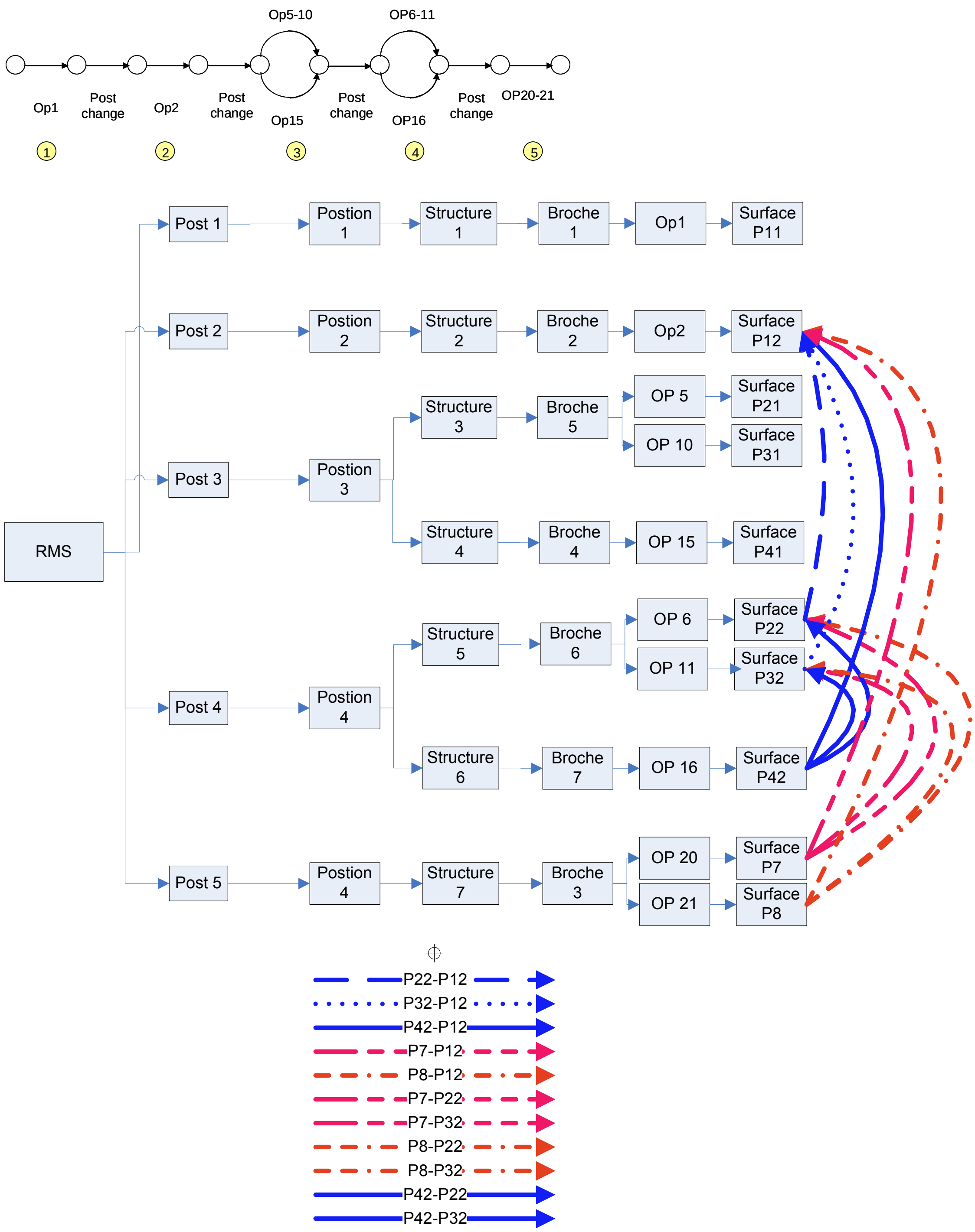


Figure 95 Possible liaisons between interacting surfaces for five post solution

Using the defined heuristics for the graphs, calculation of Internal Tolerance Condition (ITC) is done as follows:

$$ITC_{P22\text{-}P12} = \Delta L_{\text{Tooling12}} + \Delta L_{\text{Broche2}} + \Delta L_{\text{Structure2}} + \Delta L_{\text{Post2}} + \Delta L_{\text{Post4}} + \Delta L_{\text{Structure5}} + \Delta L_{\text{Broche5}} + \Delta L_{\text{Tooling22}}$$

$$= 0.030$$

$ITC_{P32\text{-}P12}$ $= \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure2} + \Delta L_{Post2} + \Delta L_{Post4} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling32}$

$= 0.030$

$ITC_{P42\text{-}P12}$ $= \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure2} + \Delta L_{Post2} + \Delta L_{Post4} + \Delta L_{Structure6} + \Delta L_{Broche6} + \Delta L_{Tooling42}$

$= 0.030$

$ITC_{P7\text{-}P12}$ $= \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure2} + \Delta L_{Post2} + \Delta L_{Post5} + \Delta L_{Structure7} + \Delta L_{Broche7} + \Delta L_{Tooling7}$

$= 0.030$

$ITC_{P8\text{-}P12}$ $= \Delta L_{Tooling12} + \Delta L_{Broche2} + \Delta L_{Structure2} + \Delta L_{Post2} + \Delta L_{Post5} + \Delta L_{Structure7} + \Delta L_{Broche7} + \Delta L_{Tooling8}$

$= 0.030$

$ITC_{P7\text{-}P22}$ $= \Delta L_{Tooling7} + \Delta L_{Broche7} + \Delta L_{Structure7} + \Delta L_{Post5} + \Delta L_{Post4} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling22}$

$= 0.030$

$ITC_{P7\text{-}P32}$ $= \Delta L_{Tooling7} + \Delta L_{Broche7} + \Delta L_{Structure7} + \Delta L_{Post5} + \Delta L_{Post4} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling32}$

$= 0.030$

$ITC_{P8\text{-}P22}$ $= \Delta L_{Tooling8} + \Delta L_{Broche7} + \Delta L_{Structure7} + \Delta L_{Post5} + \Delta L_{Post4} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling22}$

$= 0.030$

$ITC_{P8\text{-}P32}$ $= \Delta L_{Tooling8} + \Delta L_{Broche7} + \Delta L_{Structure7} + \Delta L_{Post5} + \Delta L_{Post4} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling32}$

$= 0.030$

$ITC_{P42\text{-}P22}$ $= \Delta L_{Tooling42} + \Delta L_{Broche6} + \Delta L_{Structure6} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling22}$

$= 0.018$

$ITC_{P42\text{-}P32}$ $= \Delta L_{Tooling42} + \Delta L_{Broche6} + \Delta L_{Structure6} + \Delta L_{Structure5} + \Delta L_{Broche5} + \Delta L_{Tooling32}$

$= 0.018$

The one dimensional analyses of the two possible solutions i.e. single post-multi operations and multiple posts-single operations are discussed above. The maximum value of the Internal Tolerance Condition (ITC) between any two interacting elements in the torsor chain for a kinematic configuration is the tolerance limit for that particular process plan and structure. This value should be less than the one specified /demanded by the product design specifications. In case of our studied cases the ITC (Max) for the single post solution is:

$$ITC_{Single\ post}\ (Max) = ITC_{P22\text{-}P12} / ITC_{P32\text{-}P12} / ITC_{P42\text{-}P12}$$
$$= 0.026,$$

For the multi post solution

$$ITC_{Multi\ post}\ (Max) = ITC_{P22\text{-}P12} / ITC_{P32\text{-}P12} / ITC_{P42\text{-}P12} / ITC_{P7\text{-}P12} / ITC_{P8\text{-}P12} / ITC_{P7\text{-}P22} / ITC_{P7\text{-}P32} / ITC_{P8\text{-}P22} / ITC_{P8\text{-}P32}$$
$$= 0.030$$

5 Conclusion

The selection of solutions generated in Chapter 3 requires the definition of criteria and approaches for evaluating them. Definition of the criteria for the evaluation of the generated solutions is an important step to validate the proposed approach. The range of product family, quality, cost, and time are key criteria to measure. For each of these criteria, evaluation approaches have been identified from a literature search. We can cite: the entropy proposed by O. Garro for the extended product family, the ABC approach to cost and time estimation.

Quality is measured in terms of machining tolerances of the designed kinematic chain and process plan. In the case of test quality, traditional approaches such as Δl are not directly usable for the simulation of a range on an RMS. The architecture of a RMS present structures in parallel. An adaptation of graphs generated in Chapter 3 was proposed to use the simulation approach developed by S. Tichadou, who modeled the error and geometric deviations, using a small displacement torsors. The graphical approach helped us to identify the sources of geometric deviation caused by different interacting elements.

After having studied the interacting elements in a machining process plan and kinematic structure, the sources of errors and geometrical deviations in the machining process, implementation of one dimensional simulation, we have demonstrated the applicability of the modeling approach proposed by Stephane Tichadou. One dimensional ΔL data based on machining experts is used to calculate numerical values for each chain.

Future works involves:

- analysis of the robustness and sensitivity of the defined performance indicators,
- study of the aggregation of the performance indicators.

Conclusion and Future works

Conclusion and Future works

This thesis is positioned in the domain of reconfigurable systems. It attempts to establish a link between the strategic and operational level. Also design tools at the operation level have been proposed. Our work addresses the main problem areas associated with the design and implementation of a RMS. It is directed towards the response of the problem statement:

« How to optimize the design of the manufacturing processes and reconfigurable manufacturing system while taking into account the interactions between the processes and resources, the technological constraints imposed by the part to be manufactured ?

The approach we have implemented to achieve this objective can be decomposed as follows:

- Bibliographic study on approaches and tools for design of production systems revealed that most of the existing design approaches (MSDD, PDS, Reconfigurable process planning …) are either directed towards the strategic level or else, operational level.
- Formalization of the needs and problem statement of our work,
  - Works on the design methodologies of the production systems are oriented towards two directions: a strategic level to optimize the return on investment, the second at the operational level to optimize the structure and control system. We can notice a lack of connections between these two directions.
  - Existing approaches for generating machining process plans require knowledge regarding usable production systems architectures; similarly, the approaches for architecture design of production system requires knowledge of machining process plans to be performed on them. We are faced with a paradox: the design of A requires knowledge of B and "vice versa".
  - These two constraints have motivated our work.
- Definition of a design framework acting as a link between the operational and strategic level. Based on the works of D. Cochran using axiomatic design principles to formalise the design of a production system at the strategic level, we have proposed a adaptation of the FBS approach for the its design at the operational level. Performance domain has been integrated to cater for the evaluation of the design solutions. Structuring of performance domain has been done using axiomatic design principles. The compatibility and applicability of MASON with the design of RMS based on FBS approach is shown
- Definition of an algorithmic approach to explore solutions at the operational level (co-design of machining process plans and associated kinematic configurations of RMS).
  - Based on the works regarding generation of machining process plans (machining feature, cutting tool chart, precedence relationship matrix …), we proposed an algorithmic approach for generating machining process plans by exploring all possibilities offered by RMS: multiple parallel kinematic structures machining simultaneously, ... and the objective of freeing minimum number of phases. The generation is supported by a graphical structuring of the generated solutions. Process plans can be created as variants of existing process plans already generated or in the process of being generated.

- o This generative approach can be likened to a problem of dynamic constraint satisfaction - the number of variables and constraints depends on the values taken by certain variables. The kinematic configurations required for each machining operation are identified. This approach has been implemented and then validated on 3 parts of the automotive domain.

- Definition of procedures for assessing the generated solutions,

  Based on the framework defined in Chapter 2 and on a literature review, we proposed for each evaluation criteria, one or several approaches to define and quantify it. Special attention has been deployed to evaluation criteria "quality". The existing approaches require adaptation to carry out the simulation of geometric deviations defects from the graphs generated in Chapter 3. An adaptation graph of S. Tichadou and use of simulation by Δl enabled the validation of the generated process plans.

The complete design process based on the proposed algorithm is programmed in VBA (2000 lines) having Excel as user interface. The developed code has a very less processing time. A panoramic view of the algorithmic design of RMS is shown in Figure 96.

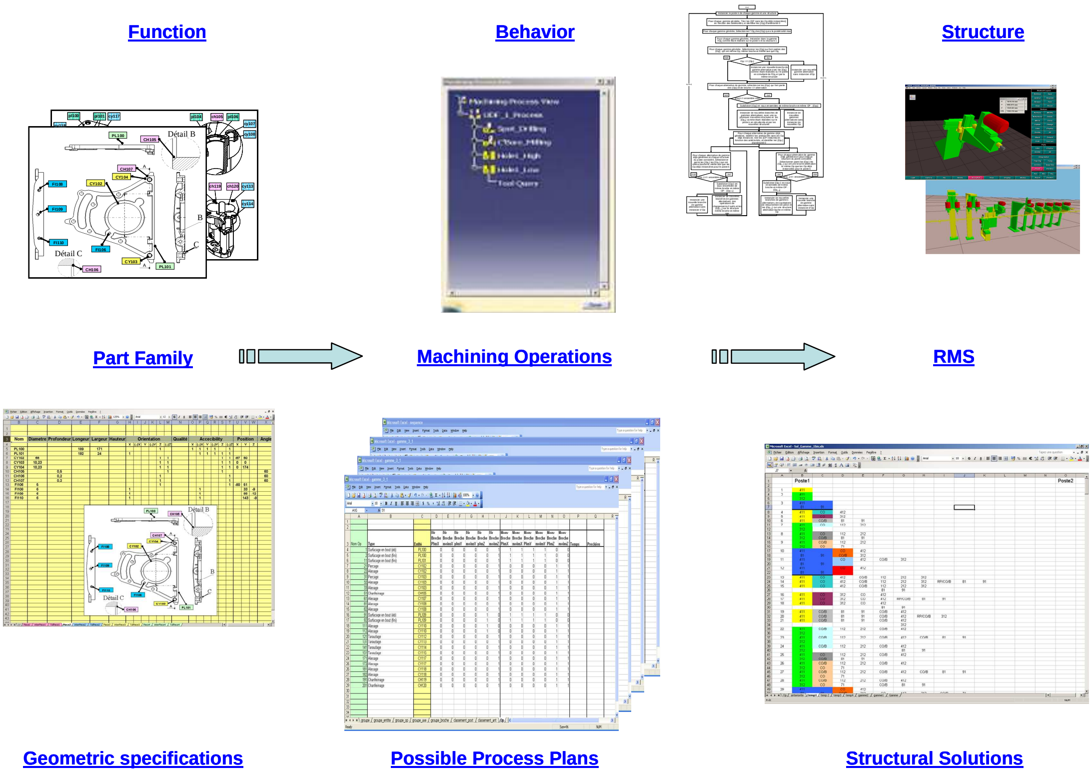


Figure 96 Design Process

We express certain criticism on the proposal:

- During the generation of process plans and kinematic configurations, the constraints linked to the part positioning have not been taken into account.

- During the generation of process plans and kinematic configurations, the constraints linked to the collision between the structures have not been treated.

- The validation of the framework proposed in chapter 2 has not been performed at the operational level.

These criticisms open different perspectives to this work. It is very important to add as perspective the coupling of the solutions exploration approach with optimization of a production system from a logistical point of view (e.g. works of A. Dolgui).

At the end, this work which was initially focused on the design of reconfigurable production system, have led to co-design of reconfigurable machining process plans and reconfigurable production systems. This point has not yet been exploited, it seems appropriate to consider at the time of reconfiguring of an existing system for manufacturing a new product: What is the process plan and what is the configuration minimizing the reconfiguration activity?

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Annexes

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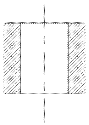
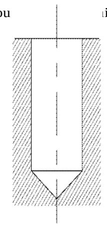
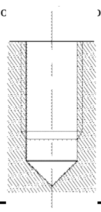
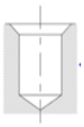
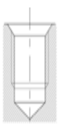
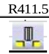
Cutting tool charts Axial features

Cutting Tool Chart / Carte Visite Hole/Trou :

Feature	Diameter D		Tol	Depth L	L Max	Material	Operation	Operation	Operation	Operation
	min	max								
Trou débouchant / Through hole 	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)	Finish Boring R429.9009013 01CB H10F	
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)			
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)			
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)			
	10	25	h7	275	10D	Steel and pig iron	Drilling (Factory Std)			
	12	125	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 390 - R390012A161 1L)	Finish Boring (CoroMill 391.38 -1 - T09 A)	
	10	270	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 391.68 - 8 - T16 A)	Finish Boring (CoroMill 391.38U-1 - 2ATP11A)	
Trou-non débouchant-fond plan-non taraudé	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)	Finish Boring R429.9009013 01CB H10F	
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)	Finish Boring R429.9009013 01CB H10F		
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F		
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F		
	10	25	h7	275	10D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F		
	12	125	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 390 - R390012A161 1L)	Finish Boring (CoroMill 391.38 -1 - T09 A)	
	10	270	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 391.68 - 8 - T16 A)	Finish Boring (CoroMill 391.38U-1 - 2ATP11A)	

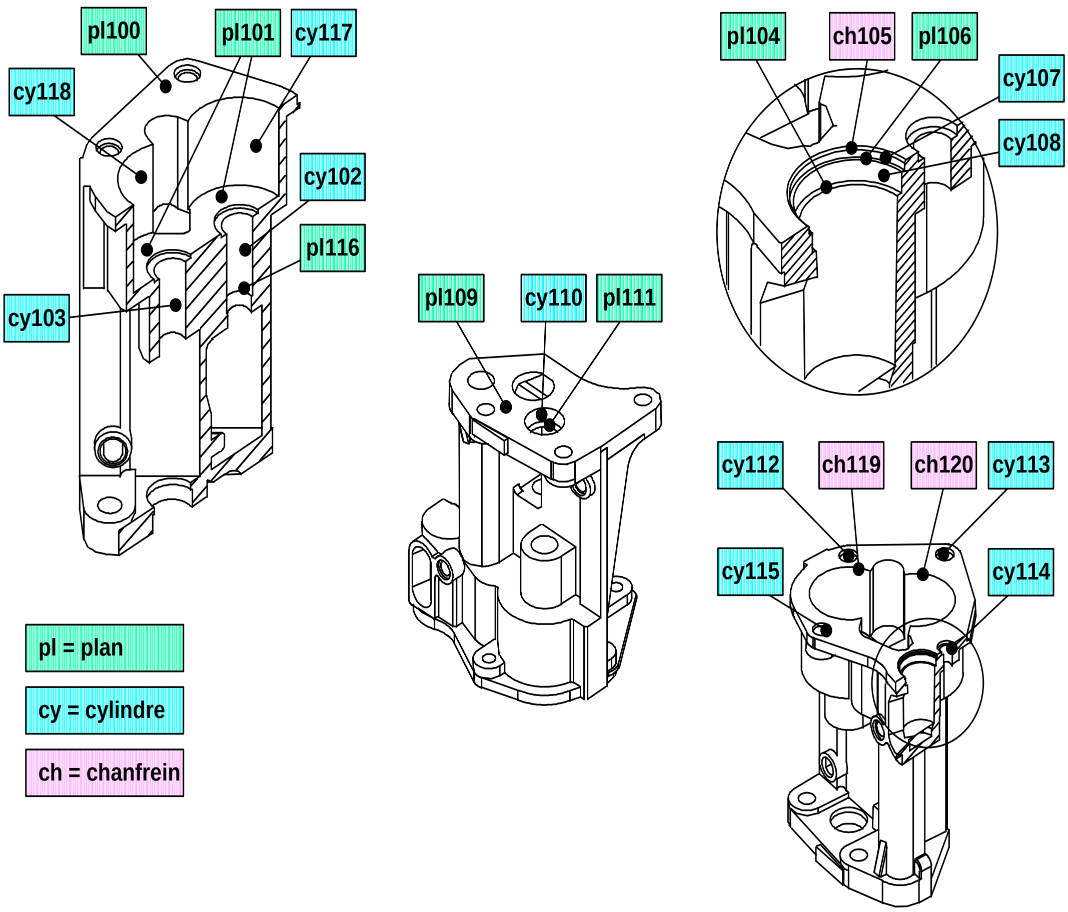
Trou-non débou ique-non taraudé 	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)		
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)			
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)			
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)			
	10	25	h7	275	10D	Steel and pig iron	Drilling (Factory Std)			
	12	125	IT9	320		All	Drilling (Factory Std)			
	10	270	IT9	320		All	Drilling (Factory Std)			
Trou-non débc onique - taraudé 	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)	Finish Boring R429.9009013 01CB H10F	
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)	Finish Boring R429.9009013 01CB H10F		
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F		
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F		
	10	25	h7	275	10D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F		
Trou-non débouchant-fond conique - non taraudé - Chanfrien 	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)	 Forming Tool Delta Cro R411.5	
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)	Finish Boring R429.9009013 01CB H10F	Forming Tool Delta Cro R411.5	
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F	Forming Tool Delta Cro R411.5	
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)	Forming Tool Delta Cro R411.5		
	10	25	h7	275	10D	Steel and pig iron	Drilling (Factory Std)	Forming Tool Delta Cro R416.2		
	12	125	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 390 - R390012A161 1L)	Finish Boring (CoroMill 391.38 -1 - T09 A)	Forming Tool Delta Cro R411.5
	10	270	IT9	320		All	Drilling (Factory Std)	Rough Boring (CoroMill 391.68 - 8 - T16 A)	Finish Boring (CoroMill 391.38U-1 - 2ATP11A)	Forming Tool Delta Cro R411.5
Trou-non débouchant-fond conique - taraudé -Chanfrien 	1.8	20	h7	166	3D	All	Centering	Drilling (DIN 340 NFE 66068)	Forming Tool Delta Cro R411.5	 Threading Tool M2-M12
	2.5	16	h7	120	3D	All	Drilling (DIN 338 NFE 66068)	Finish Boring R429.9009013 01CB H10F	Forming Tool Delta Cro R411.5	Threading Tool M2-M12
	10	25	m7	108	5D	Steel and pig iron	Drilling (Factory Std)	Finish Boring R429.9009013 01CB H10F	Forming Tool Delta Cro R411.5	Threading Tool M2-M12
	10	24	h7	200	7D	Steel and pig iron	Drilling (Factory Std)	Forming Tool Delta Cro R411.5	Threading Tool M2-M12	

Cutting tool charts – Prismatic features:

Feature	Diameter D		Tol	rε	Material	Operation	Operation	Operation	Operation
	min	max		mm					
Plane (narrow)	3	12	h11		All	Surfacing (Rough)	Surfacing (finishing)		
	1	20	h9		All	Surfacing (Rough)	Surfacing (finishing)		
Plane (non-narrow)	80	250			Steel, Pig iron	Surfacing (Rough) R260,90-080Q27-12M	Surfacing (finishing) R260,8-080Q22-12H-F		
	100	400			Steel, Pig iron	Surfacing (Rough) R260,7-100-30	Surfacing (finishing) R260,7-100-30		
Shoulder (Epoulement)	2	20		0,2-3,1	All	Surfacing (Rough) Coromill Plura R21633-02045-AC60P	Surfacing (Finish) Coromill Plura R21633-02045-AC60P		
Slot	1	40		0,2-3,1	All	Surfacing (Rough)	Surfacing (Finish)		
	2	20		0,2-3,1	All	Surfacing (Rough) Coromill Plura R21633-	Surfacing (Finish) Coromill Plura R21633-		

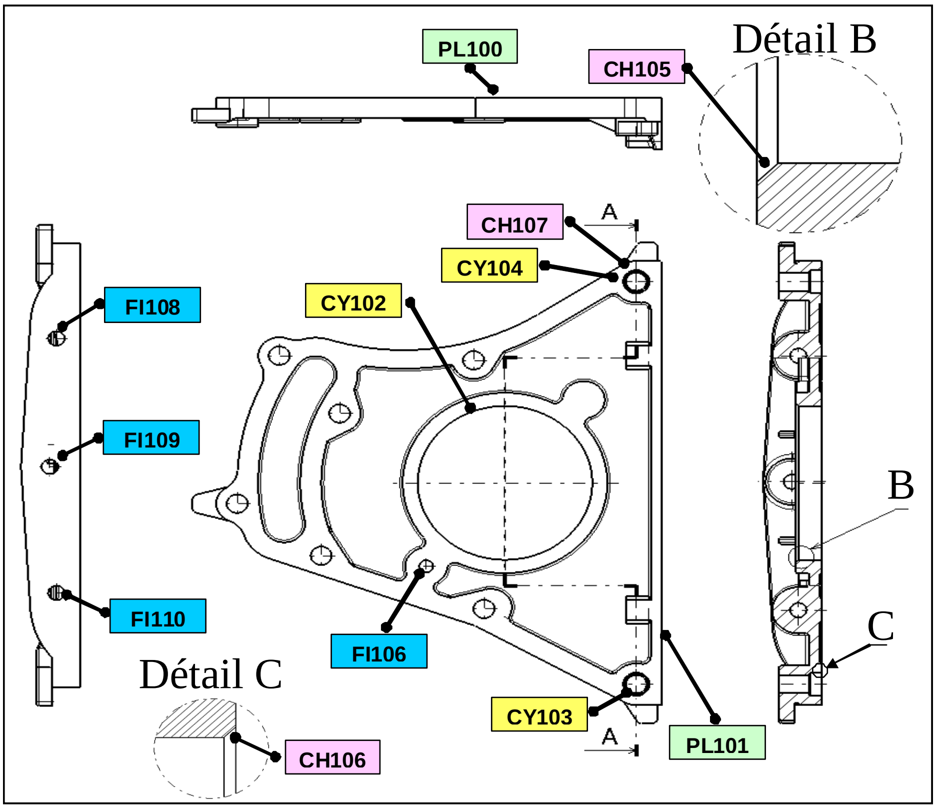
Precedence relationship matrix: part CPHC

		PL100	PL100	PL101	PL101	PL109	PL109	CY107	CY107	CY107	CY108	CY108	CY108	CY110	CY110	CY110	CY117	CY117	CY118
		1	2	7	8	9	10	13	14	15	16	17	18	19	20	21	22	23	27
PL100	1	0	1	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1
PL100	2	-1	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1
PL101	7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PL101	8	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PL109	9	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0
PL109	10	0	0	0	0	-1	0	0	0	0	0	0	0	1	1	1	0	0	0
CY107	13	-1	-1	0	0	0	0	0	1	-1	1	1	1	0	0	0	0	0	0
CY107	14	-1	-1	0	0	0	0	-1	0	-1	1	1	1	0	0	0	0	0	0
CY107	15	-1	-1	0	0	0	0	1	1	0	1	1	1	0	0	0	0	0	0
CY108	16	-1	-1	0	0	0	0	-1	-1	-1	0	1	-1	0	0	0	0	0	0
CY108	17	-1	-1	0	0	0	0	-1	-1	-1	-1	0	-1	0	0	0	0	0	0
CY108	18	-1	-1	0	0	0	0	-1	-1	-1	1	1	0	0	0	0	0	0	0
CY110	19	0	0	0	0	-1	-1	0	0	0	0	0	0	0	1	-1	0	0	0
CY110	20	0	0	0	0	-1	-1	0	0	0	0	0	0	-1	0	-1	0	0	0
CY110	21	0	0	0	0	-1	-1	0	0	0	0	0	0	1	1	0	0	0	0
CY117	22	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
CY117	23	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0
CY118	27	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY118	28	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
CY102	32	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY102	33	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY102	34	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY103	35	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY103	36	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY112	40	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY113	41	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY114	42	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CY115	43	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

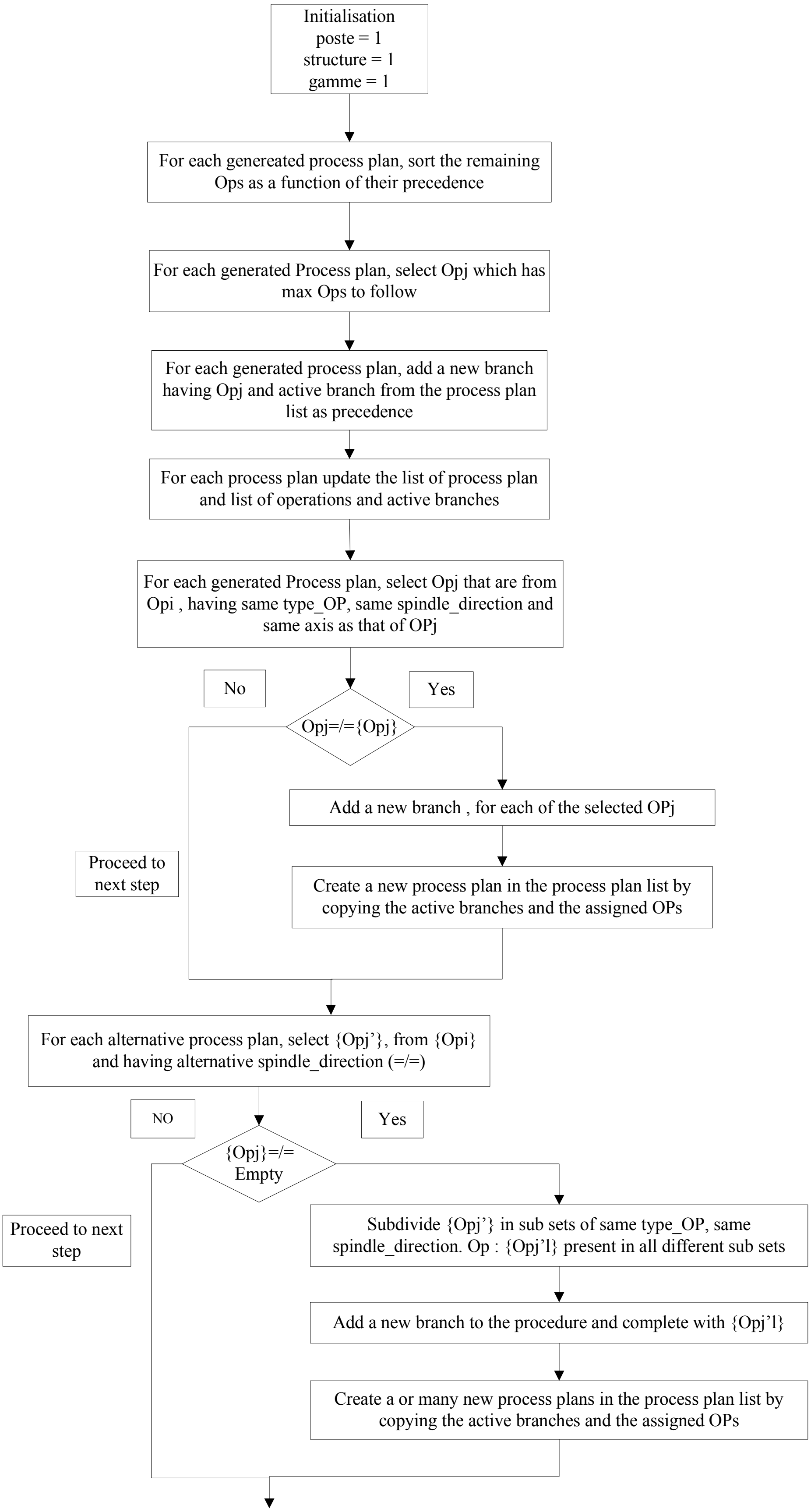


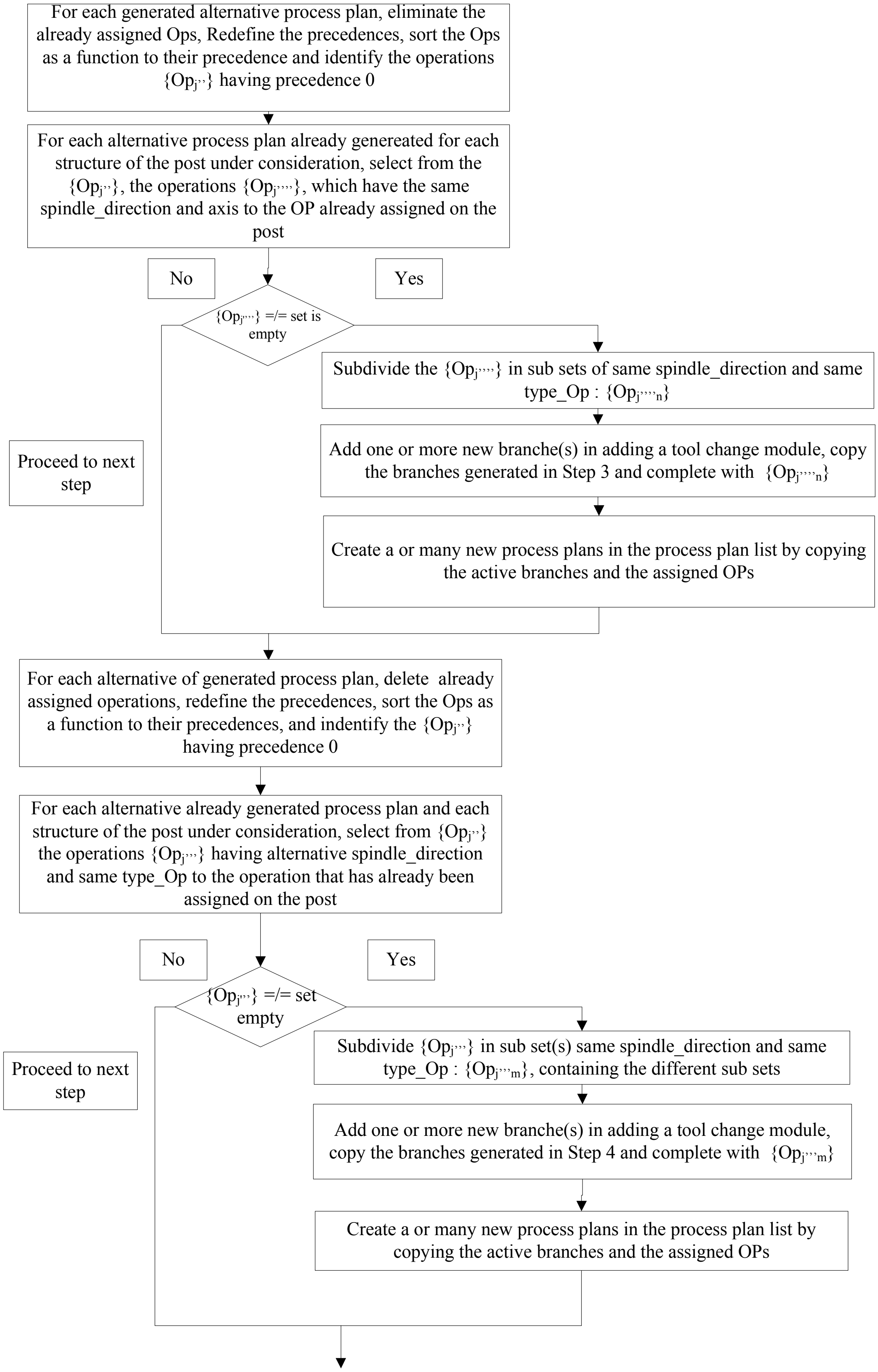
Precedence relationship matrix: part CDV

		PL 100	PL 100	PL 101	PL 101	CY 102	CY 102	CY 103	CY 103	CY 104	CY 104	FI 106	FI 108	FI 109	FI 110
		3	4	7	8	9	10	14	15	19	20	24	25	26	27
PL100	3	0	1	0	0	0	0	1	1	1	1	1	0	0	0
PL100	4	-1	0	0	0	0	0	1	1	1	1	1	0	0	0
PL101	7	0	0	0	1	0	0	0	0	0	0	0	1	1	1
PL101	8	0	0	-1	0	0	0	0	0	0	0	0	1	1	1
CY102	9	0	0	0	0	0	1	0	0	0	0	0	0	0	0
CY102	10	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
CY103	14	-1	-1	0	0	0	0	0	1	0	0	0	0	0	0
CY103	15	-1	-1	0	0	0	0	-1	0	0	0	0	0	0	0
CY104	19	-1	-1	0	0	0	0	0	0	0	1	0	0	0	0
CY104	20	-1	-1	0	0	0	0	0	0	-1	0	0	0	0	0
FI106	24	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0
FI108	25	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0
FI109	26	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0
FI110	27	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0



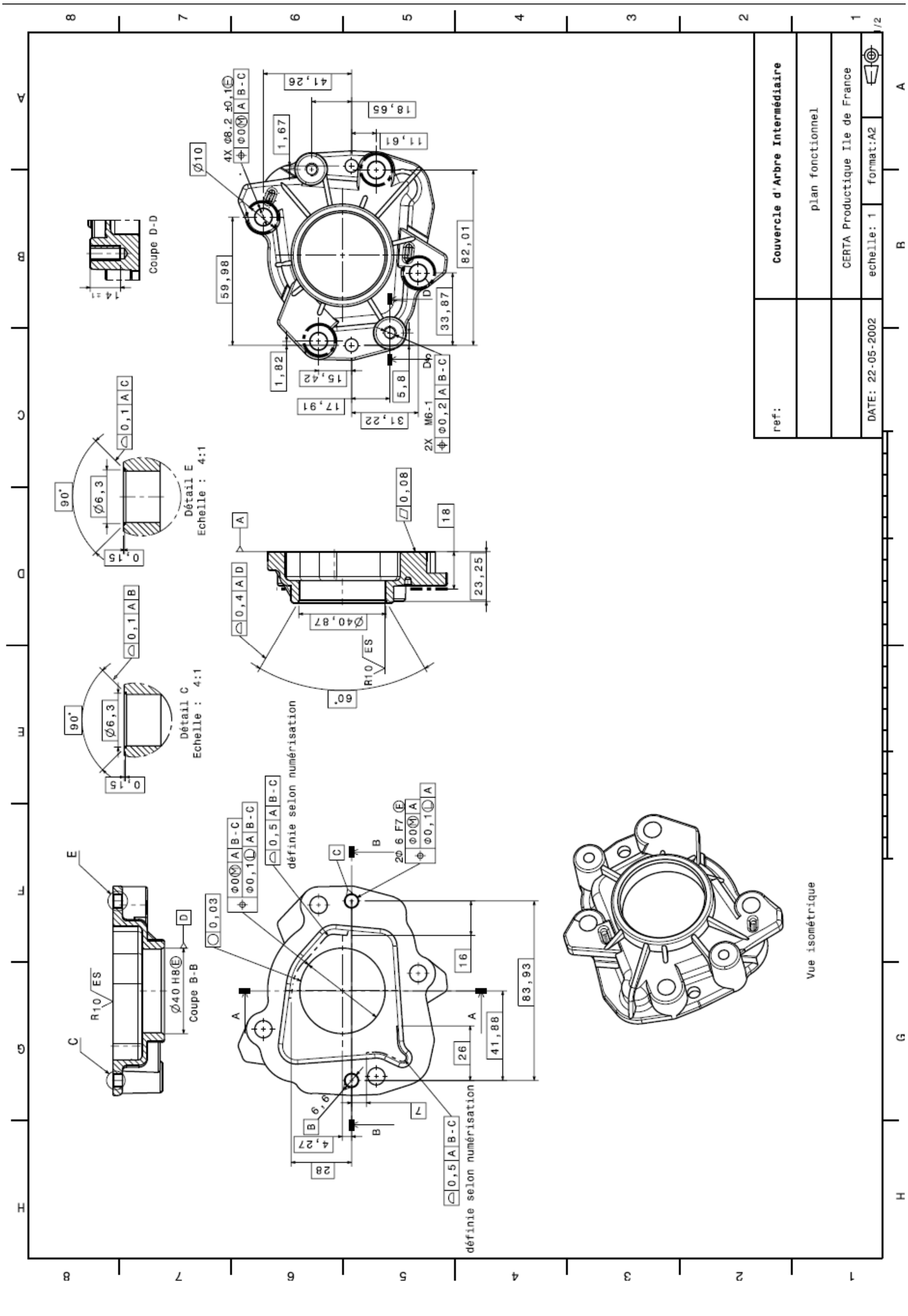
Process Plan and Kinematic Configurations Generation Algorithm




For each generated alternative process plan, eliminate the already assigned Ops, Redefine the precedences, sort the Ops as a function to their precedence and identify the operations {Opj''} having precedence 0
For each alternative process plan already genereated for each structure of the post under consideration, select from the {Opj''}, the operations {Opj'''}, which have the same spindle_direction and axis to the OP already assigned on the post
No
Yes
{Opj'''} =/= set is empty
Subdivide the {Opj'''} in sub sets of same spindle_direction and same type_Op : {Opj''',n}
Proceed to next step
Add one or more new branche(s) in adding a tool change module, copy the branches generated in Step 3 and complete with {Opj''',n}
Create a or many new process plans in the process plan list by copying the active branches and the assigned OPs
For each alternative of generated process plan, delete already assigned operations, redefine the precedences, sort the Ops as a function to their precedences, and indentify the {Opj''} having precedence 0
For each alternative already generated process plan and each structure of the post under consideration, select from {Opj''} the operations {Opj'''} having alternative spindle_direction and same type_Op to the operation that has already been assigned on the post
No
Yes
{Opj'''} =/= set empty
Proceed to next step
Subdivide {Opj'''} in sub set(s) same spindle_direction and same type_Op : {Opj''',m}, containing the different sub sets
Add one or more new branche(s) in adding a tool change module, copy the branches generated in Step 4 and complete with {Opj''',m}
Create a or many new process plans in the process plan list by copying the active branches and the assigned OPs

Annex E

Functional Plan of Part CAI



Co-conception des processus d’usinage et des configurations cinématiques d’un système de production reconfigurable

RESUME : Ces travaux s’inscrivent dans la problématique de conception des systèmes de production, ils visent plus particulièrement à répondre à la question : « Comment optimiser la conception du processus d’usinage et du système de production reconfigurable en tenant compte des interactions entre le processus et les ressources, et des contraintes technologiques imposées par les pièces à fabriquer ? » via une proposition de co-exploration des espaces de solutions processus d’usinage et configurations cinématiques du système de production. Un cadre de conception a été formalisé permettant le lien entre le niveau stratégique et le niveau opérationnel. Afin d’explorer l’ensemble des solutions au niveau opérationnel, une approche algorithmique de génération des gammes d’usinage et des configurations cinématiques a été formalisée, développée, implémentée et validée sur 3 pièces du domaine automobile. Cette approche peut être assimilable à un problème de satisfaction de contraintes dynamiques, elle exploite l’ensemble des possibilités offertes par les RMS : plusieurs structures usinant en simultanée, …. La génération est supportée par une structuration en graphe des solutions générées (Des gammes d’usinage peuvent être créées comme des variantes de gammes déjà existantes et en phase de génération). Pour la sélection des solutions générées, des indicateurs des performances ont été définis, structurés, et leurs approches d’évaluation identifiées. Une attention plus particulière a été déployée pour le critère Qualité. Une adaptation des approches existantes a été faite, afin de traiter la simulation des défauts à partir des graphes générés. Une adaptation des graphes et l’utilisation de la simulation par Δl permettent la validation des gammes générées.

Mots clés : système de production reconfigurable, machine outil reconfigurable, méthodologie de conception, gamme d’usinage, configuration cinématique

Design of the process plans and kinematic configurations of a reconfigurable manufacturing system

ABSTRACT: This work is based in the domain of the design of manufacturing systems and attempts to respond to the problem statement: “How to optimize the design process of the machining process plans and reconfigurable manufacturing systems, while taking into account: the interactions between processes and resources, the technological constraints imposed by the part to be manufactured”? This response is given via a proposal for the co-exploration of the solution space of the process plans and kinematic configurations. A design framework has been formalised which gives a link between the strategic and operational level. With an objective to explore all solutions at the operational level, an algorithmic approach for the generation of process plans and corresponding machine kinematic configurations of RMS has been formalised, developed, implemented and validated on 3 parts belonging to automobile sector. This approach can be compared to the dynamic constraint satisfaction problem, it exploits the set of possibilities offered by RMS: parallel structures, simultaneous machining… The process of generation of process plans is supported by representation of the generated solutions in the form of graphs. For the selection the generated solutions, performance indicators have been defined, structured, and their evaluation approach identified. A particular attention was given to the criterion of quality. An adaptation of the existing approaches was carried out and simulation of geometric deviation in the generated solutions was done. Generated solutions were adapted to be graphically represented and used for the simulation by Δl. This was done to validate the obtained results.

Keywords : Reconfigurable Manufacturing Systems, reconfigurable manufacturing tool, design methodology, process plans, kinematic configurations

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