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Contribution to the co-development of products and their reconfigurable production systems

Paul Stief

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ÉCOLE DOCTORALE SCIENCES DES MÉTIERS DE L'INGÉNIEUR
Laboratoire de Conception, Fabrication et Commande – Campus de Metz

THÈSE

présentée par : **Paul Leonard STIEF**

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préparée à : **École Nationale Supérieure d'Arts et Métiers**

Spécialité : **Génie industriel**

Contribution à la co-conception de produits et de leurs systèmes de production reconfigurables

THÈSE dirigée par :
Pr. DANTAN Jean-Yves

et co-encadrée par :
MCf. ETIENNE Alain et Pr. SIADAT Ali

Jury

M. Alexandre DOLGUI, Professeur, LS2N, IMT Atlantique

M. Michel ALDANONDO, Professeur, Mines Albi-IMT, Université de Toulouse

M. Frédéric DEMOLY, Maître de Conférences (HDR), ICB-COMM,
Université de technologie de Belfort-Montbéliard

Mme. Gisela LANZA, Professeur, WBK, KIT Karlsruhe Institute of Technology

M. Jean-Yves DANTAN, Professeur, LCFC, Arts et Métiers Metz

M. Alain ETIENNE, Maître de Conférences, LCFC, Arts et Métiers Metz

M. Ali SIADAT, Professeur, LCFC, Arts et Métiers Metz

M. Guillaume BURGAT, Manager Avant Projet – Manufacturing Engineering,
thyssenkrupp Presta France S.A.S.

Président
Rapporteur
Rapporteur

Examinatrice
Examineur
Examineur
Examineur
Invité

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The General Director of Arts et Métiers authorized the writing of this dissertation in two languages: English and French. For this reason, the manuscript comprises an extended summary in French language (without figures) and a detailed description of the research in English (with figures).

Résumé étendu en Français

Introduction et présentation des questions de recherche (Preface and Chapter I)

Les travaux de thèse présentés dans ce manuscrit ont été réalisés dans le Laboratoire de Conception, Fabrication et Commande (LCFC) des Arts et Métiers, au sein du campus de Metz. La thèse fait partie de la chaire de recherche industrielle sur l'homme au centre du système de production – systèmes de production reconfigurables, sûrs et performants. Cette chaire s'adresse à quatre défis différents, dont le deuxième (en gras) est le cadre de cette thèse :

1. Conception sûre des systèmes de production ;
2. **Adaptabilité et reconfigurabilité des systèmes de production ;**
3. Optimisation des temps non productifs ;
4. Caractérisation des performances – fouille de données.

Les travaux de thèse ont été menés en étroite coopération avec notre partenaire industriel, équipementier dans le domaine d'automobile. Cela permettait la mise en place d'une méthodologie de recherche appliquée cyclique qui consiste en trois étapes : développer – expérimenter – analyser (comparable à la roue de Deming). Par cette approche itérative, les concepts nouvellement développés ont été testés et améliorés avec des cas d'études industriels tout au long de la recherche. La problématique de recherche peut être cernée par deux points de vue différentes. D'un côté le point de vue industrielle, et de l'autre côté le point de vue académique.

Du côté industriel, le marché est marqué par une tendance de la production industrielle en masse – caractérisée par des grandes tailles de lots de production, une variété faible et des cycles de vie longues – vers une production artisanale sur l'échelle industrielle – caractérisée par des petites tailles de lot de production, une variété importante et des cycles de vie courtes. Afin de faire face à cette problématique industrielle, les entreprises ont identifiées le besoin d'une production agile et reconfigurable afin de justifier les investissements importants dans les unités de production ainsi que pour avoir le retour d'investissement. A cela s'ajoute l'environnement spécifique de notre partenaire industriel : celui d'un fournisseur dans l'automobile. Ce secteur est très concurrentiel avec une compétition d'un côté entre les différents fournisseurs et de l'autre côté, également entre les manufacturiers de voitures qui, en position de force, imposent leurs exigences aux fournisseurs. En conséquence, l'agilité et la reconfigurabilité des systèmes de production deviennent des éléments clés pour assurer la compétitivité de l'entreprise.

Du côté académique, le concept d'agilité ainsi que ses éléments annexes comme flexibilité, changeabilité, reconfigurabilité, convertibilité etc. ont été discutés dans une plénitude de publications. Il est à noter ici, que dans ces travaux de recherche le terme agilité est utilisé dans son sens technique (agilité des éléments du système de production) et ne pas dans le sens organisationnel ou sur le plan de l'infrastructure

(supply-chain, management, internet des objets). Afin de clarifier les notions des termes employés dans le suivant, les définitions suivantes sont introduites :

- La **flexibilité** est la capacité intrinsèque d'un élément du système de production (ex. poste de travail, module, cellule, ...) d'absorber des changements imposés par l'extérieur sans besoin de modification ;
- La **reconfigurabilité** est la capacité technique d'un élément du système de production (ex. poste de travail, module, cellule, ...) de pouvoir être adapté aux changements imposés par l'extérieur par modification de ses caractéristiques ;
- L'**agilité** est la capacité générique d'un système de production de s'adapter aux changements imposés par l'extérieur. Ces changements peuvent représenter des variations de demande ou produits. L'agilité englobe le potentiel global d'adaptation du système de production incluant ses capacités de flexibilité plus celles de reconfigurabilité.

Afin de localiser les travaux de thèse dans le contexte de la recherche actuelle sur les aspects de la reconfigurabilité, les grands axes de recherche identifiés en littérature sont présentés ensuite. Concernant l'assemblage reconfigurable, les cinq axes de recherche suivants sont présentés :

- **La conception pour l'assemblage** (*Design for Assembly - DfA*) car la conception du produit a des répercussions importantes sur le système de production et détermine sa conception ;
- De nouveaux processus d'assemblage et machines remplaçant la force de travail humaine qui est souvent utilisée dans les systèmes d'assemblage ;
- La modularisation et standardisation pour accroître la réutilisabilité des éléments du système d'assemblage pour différents produits à la fin d'un cycle de production ;
- La programmation robotique automatisée et le contrôle intelligent pour réaliser l'adaptation logicielle en reconfiguration ;
- La modélisation et la simulation intégrées qui fournissent une aide à la décision car la reconfiguration nécessite une décision continue de choisir la meilleure solution.

Complémentaire à ces axes concernant l'assemblage reconfigurable (*reconfigurable assembly*), d'autres axes ont été identifiés en littérature concernant la fabrication reconfigurable (*reconfigurable manufacturing*) :

- **La combinaison de systèmes reconfigurables avec d'autres paradigmes de production** comme par exemple la fabrication Lean pour enrichir les avantages de RMS avec d'autres caractéristiques ;
- **L'élaboration d'une méthodologie de conception systématique** pour des systèmes reconfigurables répondant à la nécessité de nouvelles méthodologies de conception, à la nécessité de déterminer la granularité du système et à la nécessité de méthodes aidant les industriels à passer de systèmes non configurables à des systèmes reconfigurables ;
- La conception des configurations lorsque le nombre de variables reconfigurables (p. ex. convoyeurs, appareils, etc.) est important ;
- La conception des systèmes de contrôle pour réaliser les adaptations en temps réel et la conception ouverte d'architecture de contrôle pour réaliser des infrastructures modulaires.

Dans les études les plus récentes concernant la recherche sur les systèmes reconfigurables, cinq volets de recherche ont été identifiés qui regroupent la plupart des activités de recherche actuelles.

- Volet 1 : Évaluation du niveau de reconfigurabilité ;
- Volet 2 : Analyse des caractéristiques du système reconfigurable, c'est-à-dire la modularité, l'intégrabilité, la capacité d'être diagnostiqué, la convertibilité, l'évolutivité et la personnalisation ;
- Volet 3 : Analyse des performances des systèmes reconfigurables ;
- **Volet 4 : Recherche appliquée et applications sur le terrain ;**
- Volet 5 : Reconfigurabilité vers l'industrie 4.0 objectifs.

À l'aide des orientations de recherche qui ont été identifiées auparavant, les travaux de thèse présentés ci-après sont situés dans le volet de recherche 4 (recherche appliquée) et aborde les sujets suivants :

- **Conception pour l'assemblage (DFA) ;**
- **Combinaison de RMS avec d'autres paradigmes de production ;**
- **Développement d'une méthodologie de conception systématique pour RMS.**

Ceci prouve que les questions de recherche présentées ci-après entrent parfaitement dans les volets de recherche actuels et abordent les questions qui sont d'intérêt autant pour la recherche que pour le partenaire industriel représentant le besoin industriel.

Les concepts d'agilité, de flexibilité et de reconfigurabilité sont bien définis et analysés dans la littérature de recherche d'aujourd'hui. Cependant, leur mise en œuvre dans la pratique industrielle n'est pas souvent réalisée, les études de cas se limitent souvent aux cas éducatifs. En s'adressant au manque de recherche appliquée et en cohérence avec les enjeux industriels, le périmètre de recherche global est défini par la question de recherche suivante :

Comment analyser, mesurer et augmenter l'agilité d'un système de production ?

Dans ce périmètre, l'accent est mis sur la reconfigurabilité dans le contexte de l'agilité telle que définie précédemment. La question clé englobant la recherche présentée est définie comme suit :

Comment concevoir un système de production reconfigurable compte tenu des familles de produits et de leur assemblage en abordant les aspects de la coévolution ?

A partir de cette question clé, un ensemble d'objectifs est dérivé. Ces objectifs guident la recherche. Ils sont regroupés dans trois objectifs principaux, chacun abordant les trois aspects de coévolution : produit, processus et système de production.

- **Objectif 1** : Permettre l'analyse des produits et des familles de produits caractérisés par une variété de produits ;
 - **Objectif 1.1** : Permettre l'analyse et la comparaison structurelle des produits et de leurs familles ;
 - **Objectif 1.2** : Permettre l'analyse et la comparaison d'assemblage des familles de produits.

Objectif 1 contient la modélisation du produit. Généralement connu, un modèle est une représentation simplifiée de la réalité, contenant exactement l'information nécessaire

pour ses cas d'utilisation. Ainsi, il pose le sous-sol pour objectif 2 et objectif 3 qui sont des cas d'utilisation des modèles développés dans l'objectif 1.

- **Objectif 2** : Permettre l'identification ou l'amélioration des familles de produits
 - **Objectif 2.1** : Définir des indicateurs pour la similarité de conception de produits
 - **Objectif 2.2** : Définir des indicateurs pour la similarité d'assemblage

Objectif 2 contient la génération de familles de produits et leur amélioration. L'amélioration se traduit par une similitude structurelle et d'assemblage. Cet objectif aborde la deuxième partie de la question clé compte tenu des familles de produits, de leur conception et de leur assemblage.

- **Objectif 3** : Permettre la génération préliminaire de plans d'assemblage alternatifs
 - **Objectif 3.1** : Modéliser et formaliser des contraintes d'antériorités de l'assemblage
 - **Objectif 3.2** : Modéliser et formaliser des séquences d'assemblage basées sur la stratégie de mise en position
 - **Objectif 3.3** : Permettre la comparaison des séquences d'assemblage pour les familles de produits en vue d'un système multi-produit

Objectif 3 aborde la première partie de la question clé qui est de savoir comment concevoir un système de production reconfigurable. Il contient des méthodes pour générer un ensemble de solutions possibles pour le système de production, dans le respect d'un ensemble de contraintes prédéfinie.

Compte tenu d'un ensemble de produits, l'entrée est l'information sur le produit et l'assemblage (p. ex. dessins techniques, fichiers CAO, listes de parties, ...). A partir de ceux-ci, les modèles de produits illustrés dans le tronc sont générés, à commencer par le Datum Flow Chain (DFC). Ce graphe orienté représentant la structure du produit par ses composants est enrichie d'informations d'assemblage et d'informations sur les fonctions techniques. Depuis cette version enrichie, l'architecture physico-fonctionnelle est générée (PHARE). Ces modèles de produits appartiennent à objectif 1 et sont modélisés avec la méthodologie développée à cette fin. Sur la base de ces modèles, à l'aide de combinaisons d'entre eux, les buts définis dans l'objectif 2 et l'objectif 3 peuvent être atteints, en suivant les branches de l'arbre.

Pour atteindre l'objectif 2, l'analyse de similitude avec quatre nouveaux indices de similarité, basés sur les modèles de produits PHARE et DFC, permet la comparaison structurelle et d'assemblage des familles de produits tenant compte de la variété des produits et des composants. L'analyse de similarité peut être utilisée à deux fins : soit pour des améliorations de conception de produits (DFA) en appliquant une méthodologie itérative pour améliorer les valeurs de similitude modifiant les choix de technologie de conception et d'assemblage du produit. Ou la similarité peut être utilisée pour l'identification de la famille de produit, recueillant des produits avec des valeurs élevées de similarité.

En ce qui concerne l'objectif 3, l'identification des antériorités est basée sur le modèle du DFC enrichi. Les stratégies de mise en position (MiP) peuvent être dérivées des MiP candidates qui sont identifiées basées sur une analyse conjointe du modèle du DFC enrichi et du PHARE. Les antériorités ensemble avec l'information des MiP mènent

finalement à la génération des plans de séquence d'assemblage. Pour les lignes d'assemblage multiproduits, une méthode de comparaison des plans de séquences d'assemblage est introduite. Il peut être indiqué, qu'une fois la partie de modélisation terminée, soit l'objectif 2 peut être réalisé, soit l'objectif 3. Ou les deux peuvent être combinés, l'approche étant réglable pour différents cas d'utilisation.

Recherche bibliographique (Chapter II)

La recherche bibliographique est développée suivant deux grands axes : d'un côté les publications qui traitent des approches complètes de co-conception de produit-processus-système de production, et de l'autre côté des publications qui traitent des éléments spécifiques de chaque objectif de recherche.

Concernant les approches complètes, cinq différent

- i. Co-conception pour l'assemblage automatisé ;
- ii. Conception intégrée de familles de produits et leur système d'assemblage ;
- iii. Graphes de liaison et leur utilisation pour la planification des opérations et séquences d'assemblage (Figure II.3) ;
- iv. Planification de l'assemblage et conception des systèmes avec des assemblages minimaux ;
- v. Cladistiques pour la coévolution de produit et système de production.

L'analyse de ces cinq approches pour la conception intégrée des produits, (des processus) et du système de production a montré que les anciennes approches, initialement dédiées à la conception automatisée et flexible des systèmes de production, ne sont pas adaptées aux nouveaux contextes industriels marquées par l'augmentation de la variété des produits et des composants. Par conséquent, un examen plus précis de la littérature est effectué en suivant qui examine les méthodes et les modèles existants pour chaque objectif de recherche.

Objectif 1.1 : Permettre l'analyse et la comparaison structurelle des produits et de leurs familles

Trois modèles de produit sont souvent utilisés pour la modélisation de produits. Ce sont les cladistiques, les graphes de liaison et le Datum Flow Chain (DFC, « chaînes de propagation de références »). Un résumé des approches utilisant ces trois modèles est fourni dans Table II.1. Les différentes approches ont été évalué concernant trois critères, correspondant à l'objectif de recherche :

- i. Le modèle doit être insensible à la variété des composants du produit, ce qui signifie que les variations du nombre et du type des composants ne doivent pas avoir d'impact sur le modèle du produit ;
- ii. Il doit contenir un maximum d'informations sur l'assemblage du produit, par exemple la mise en position ou la technologie d'assemblage, et si ce n'est pas le cas leur intégration au modèle devrait être possible ;
- iii. Il doit être facile applicable et permettre idéalement une implémentation logique, du moins partiellement.

Aucun des modèles satisfait entièrement les trois critères. Cependant, le DFC a été identifié comme modèle le plus adapté au besoin. Il contient non seulement des informations quantitatives, mais aussi qualitatives. Par contre, il est soumis aux changements de nombre et de type des composants et n'a pas souvent été utilisé pour la représentation des familles de produits et de parties et d'une variante et une analyse de variation au sein de ces familles.

Objectif 1.2 : Permettre l'analyse et la comparaison de l'assemblage des familles de produits.

L'examen de la littérature concernant les modèles de produits a souligné qu'il n'existe aucun modèle de produit qui intègre déjà l'information d'assemblage. Ainsi, cette information doit être ajoutée pour répondre à la demande de recherche objectif 1.2. Pour ajouter l'information et les connaissances d'assemblage, un cadre est nécessaire qui définit ceux-ci. Ce cadre est fourni par une taxonomie qui doit assurer la compatibilité des connaissances et de l'information avec le modèle produit (DFC a été identifié en tant que point de départ) et une classification qui définit les éléments (données) de connaissances et d'informations. Deux exigences doivent être remplies : la classification doit être suffisamment exhaustive pour englober toutes les données d'assemblage nécessaires à l'application industrielle et la taxonomie doit être compatible avec le modèle du produit. En même temps, les deux doivent être suffisamment flexibles pour pouvoir être adaptés aux cas d'utilisation changeants, à l'évolution technologique et aux évolutions des modèles de produits. La Table II.3 donne les références analysées et leur périmètre. Pour résumer, plusieurs références sur les processus d'assemblage et les opérations existent, mais aucune d'entre elles ne propose une vision exhaustive des opérations et une taxonomie applicable au génie mécanique. Néanmoins, la série DIN 8593 semble un bon point de départ pour la conception d'une taxonomie et d'une classification utilisables pour ces travaux de recherche et compatibles avec le modèle de produit.

Objectif 2.1/2.2 : Définir des indicateurs pour la similarité de conception de produits et des technologies d'assemblage

Comparer des produits signifie l'évaluation des similarités de produit. Sur la base de cette évaluation, soit il est possible de regrouper des produits ou non (décisions de regroupement/clustering) soit des potentiels d'amélioration, en termes de similarité et de standardisation, peuvent être identifiés en essayant d'augmenter les valeurs des indicateurs de similarité. Plus en détail, au niveau de la famille des produits, les assemblages diffèrent principalement en deux caractéristiques principales : le nombre de composants et leurs types (c'est-à-dire mécanique, électrique, électronique). Dans ce cas, l'analyse de similarité vient, d'une part, identifier les familles à travers une multitude de produits différents, et d'autre part améliorer la conception d'un produit pour une meilleure similarité au sein d'une famille de produits.

Cependant, la mesure de similarité, telle qu'elle est présentée dans la littérature, est marquée par un large éventail de définitions et de méthodes. L'analyse des indices de similarité (Table II.4) a révélé qu'il y a un manque de recherche concernant l'identification de composants similaires dans les familles de produits qui se caractérisent par une variété partielle. Ces composants similaires pourraient être assemblés avec la même installation du système de production, ce qui signifie qu'une similarité basée sur le critère « exactement pareil » n'est pas nécessaire et pourrait être un cas de sur-ingénierie. De plus, une comparaison composant-composant devient plus complexe avec l'augmentation du nombre de composants.

En effet, les assemblages mécaniques complexes avec différents nombres de composants sont compliqués à comparer avec les indices basés sur les composants mentionnés dans Table II.4. En raison de l'hétérogénéité, l'efficacité d'un modèle uniquement basé sur les composants est incertaine car il a besoin d'une analyse de

compatibilité (une autre comparaison d'un à un). Les indices de similarité permettant la comparaison de la variété des produits, y compris la variété des composants, doivent être suffisamment détaillés pour donner une évaluation précise de la similitude et pour souligner les potentiels d'amélioration. Mais, en même temps, ils doivent être assez abstraits pour ne pas être touchés par une variété raisonnable, le critère « exactement pareil » étant trop strict.

Objectif 3.1 : Modéliser et formaliser les contraintes d'antériorités de l'assemblage

Les contraintes d'antériorité jouent un rôle essentiel dans la détermination des séquences d'assemblage. Elles limitent la multitude de possibilités d'ordonnancer la réalisation des liaisons mécaniques d'un produit. On peut distinguer deux groupes de contraintes : d'un côté les contraintes d'antériorité discriminantes qui sont les contraintes nécessaires pour assurer la faisabilité d'un assemblage (par exemple l'accessibilité). Et de l'autre côté les contraintes d'antériorité supplémentaires qui ne sont pas essentielles (par exemple le poids ajouté).

Les deux, contraintes discriminantes et supplémentaires doivent être représentées par le modèle choisi. En conséquence, l'analyse de la bibliographie se focalise sur les méthodes d'expression des contraintes d'antériorité (Table II.5). En résultat, des expressions logiques sont utilisées largement. En plus, des contraintes d'antériorité exprimées par opérateurs logiques peuvent être partiellement déduites des graphes de liaison. La modélisation avec des expressions logiques assure une certaine flexibilité du modèle qui permet d'ajouter des contraintes supplémentaires si nécessaire et le modèle logique peut à chaque instant être traduit dans un graphe orienté d'antériorité.

Objectif 3.2 : Modéliser et formaliser des séquences d'assemblage basées sur la stratégie de mise en position

En plus des contraintes d'antériorité, qui sont idéalement limitées au minimum vital pour ne pas réduire inutilement l'espace de solutions, des stratégies d'ordonnement peuvent être appliquées. Une approche prometteuse est l'identification des éléments de mise en position (MiP) nécessaires pour l'assemblage et leur ordonnancement. De là, des stratégies minimisant la réorientation ou le repositionnement peuvent être appliquées. En outre, dans le contexte des lignes d'assemblage multiproduits, la mise en position joue un rôle important pour la performance du système de production. Des dispositifs de MiP dédiés ou des choix de localisation spécifiques aux produits restreignent la flexibilité du système de production générant des besoins supplémentaires et évitables de changement.

Les références bibliographiques ont été examinées concernant mise en position et maintien en position afin de déterminer si des approches existent qui les utilisent pour déterminer les séquences d'assemblage et qui considèrent la mise en position dans le contexte d'un assemblage agile. Ce résultat guide la poursuite de la recherche soit vers une adaptation d'une approche existante, soit vers un développement complètement nouveau. Ainsi, la documentation sur la MiP et, plus généralement sur le fixturing (c.-à-d. MiP et maintien) est examinée en ce qui concerne la question si une stratégie de MiP peut être dérivée des concepts existants. De plus, il s'agit d'examiner les travaux existants sur la classification et la description des stratégies de MiP. La question est

donc de savoir si un nouveau concept de MiP, de leur identification et de leur application sur les systèmes d'assemblage doit être développé.

La littérature concernant ses aspects est très diversifiée en se focalisant sur différents thématiques très spécifiques, qui sont regroupés dans le tableau II.6. On peut constater qu'aucune des publications n'a permis d'identifier l'importance des stratégies de maintien et de mise en position pour un système de production adaptable. Aucune application n'a été proposée qui considère la MiP comme une partie élémentaire pour la viabilité des systèmes de production multiproduits face aux composants et à la variété des produits.

Objectif 3.2 : Modéliser et formaliser des séquences d'assemblage basées sur la stratégie de mise en position

Une façon tout à fait instinctive de comparer plusieurs séquences d'assemblage est la recherche de parties communes dans la séquence d'assemblage. La recherche de la plus longue sous-séquence commune (LCS) et la plus courte séquence englobante (super-séquence) commune (SCS) sont des méthodes qui ont été question de la recherche en mathématiques et en informatique pendant depuis un certain temps. Cependant, leur application à la comparaison de séquences d'assemblage est un domaine de recherche récent. Seules quelques applications ont pu être trouvées dans la littérature. Elles sont résumées dans le tableau II.7. En fait, l'utilisation du principe LCS/SCS sur les problèmes de comparaison de séquences semble un moyen efficace d'identifier les parties séquences communes et distinctes. Il s'agit d'une question importante dans la conception de chaînes d'assemblage multiproduits.

L'une des lacunes des approches évaluées est leur orientation vers la fabrication et non l'assemblage. L'autre est que la variété des composantes n'est pas prise en compte parce que les critères de comparaison proposés sont des comparaisons un à un de pièces ou de stations. En ce qui concerne la comparaison un à un des stations, il n'est pas détaillé comment la capacité d'adaptation des stations peut être incluse. Pour conclure, l'application des méthodes LCS/SCS à l'ensemble d'un système d'assemblage multiproduits n'a pas encore été prouvée. Il convient d'étudier quels aspects de ces modèles pourraient être appliqués sur la question de recherche présentée.

Axes de développement

Les différents axes de développement, qui sont adressés par les nouveaux modèles et méthodologies présentés dans les sections suivantes, sont résumés par objectif de recherche :

- Objectif 1.1 - Comparaison structurelle : Parmi les modèles et applications examinés, le DFC est celui qui a le plus de potentiel. Pour cette raison, il a été identifié comme point de départ pour un nouveau modèle de produit. Néanmoins, certaines adaptations sont nécessaires pour obtenir une nouvelle représentation. Cette nouvelle représentation hybride est dérivée du DFC qui permet la comparaison structurelle et fonctionnelle des familles de produits avec la variété de produits et de composants (Chapter III).
- Objectif 1.2 - Taxonomie et classification de l'assemblage : Aucun modèle de produit existant ne comprend l'information d'assemblage. Concernant les classifications et taxonomie, la série DIN est la plus détaillée et peut être utilisée comme point de départ. En plus, une nouvelle taxonomie est présentée qui est

adaptée aux modèles qui sont développés pour répondre aux questions de recherche. Cette taxonomie répond en même temps aux besoins industriels concrets et à la demande d'être suffisamment adaptable pour d'autres cas d'utilisation (Chapter III).

- Objectif 2.1/2.2 - Analyse de similarité : Les méthodes d'analyse de similarité existantes présentent des lacunes. Elles ne considèrent la variété des produits en raison de leur orientation sur les composants. En outre, les opérations ou les technologies d'assemblage sont très rarement prises en compte. Par conséquent, de nouveaux indices d'assemblage doivent être développés, traitant de la variété des produits et de son assemblage (Chapter IV).
- Objectif 3.1 - Contraintes de préséance du modèle : Il existe de nombreuses méthodes différentes pour modéliser les contraintes d'antériorité. Le plus commun est l'utilisation d'expressions logiques. L'approche basée sur des graphes de liaison semble être adaptée au problème actuel. Les opérateurs logiques sont adaptables à tous les cas et peuvent être traduits plus tard en graphes orientés d'antériorité pour une exploitation ultérieure (Chapitre V).
- Objectif 3.2 - Stratégies de mise en position et séquences d'assemblage : L'accent a été mis sur les stratégies MiP. Les publications sont très hétérogènes traitant de questions très spécifiques. Aucune méthode ayant un réel potentiel de localisation de la définition de stratégie n'a pu être identifiée. Ainsi, dans les travaux suivants, une toute nouvelle façon d'identifier et d'utiliser la MiP dans les systèmes d'assemblage est développée (Chapter V).
- Objectif 3.3 - Comparaison de séquences d'assemblage : Outre les approches SCS/LCS, aucun autre concept n'a été identifié pour la comparaison des séquences d'assemblage. Même si l'application complète de ces approches est douteuse, leurs critères peuvent être adaptés pour une utilisation sur les modèles nouvellement développés (Chapitre V).

Pour conclure, un examen détaillé de la documentation sur les méthodes et les approches existantes a été présenté. Toutes les références ont été examinées en regard de leur aptitude en ce qui concerne les questions de recherche présentées. Les lacunes ont été mises en avant ainsi que les concepts ayant un potentiel, même partiellement, intégrés dans la méthodologie nouvellement développée. Les sections suivantes détaillent maintenant les concepts nouvellement développés et leurs applications.

Modéliser produit et processus pour une variété de produits (Chapter III)

Dans cette section, les deux modèles pour la modélisation de produit sont introduits. Ils reposent sur le DFC. Celui représente la structure physique du produit en représentant les composants en tant que nœuds et les liaisons mécaniques en tant qu'arcs entre les nœuds. L'orientation des arcs indique une relation de positionnement. Le nœud d'où l'arc part positionne le nœud où l'arc entre. En plus de cette relation de positionnement, le DFC contient également le nombre de degrés de liberté qui sont éliminés par la liaison mécanique.

Cette modèle de base est enrichi avec deux éléments afin de générer un nouveau modèle de produit : l'information des technologies d'assemblage utilisées pour réaliser une liaison mécanique et l'information auquel groupe fonctionnel appartient le composant.

Afin de déterminer l'appartenance d'un composant à un groupe fonctionnel, un référentiel de fonctions techniques doit être défini. Ce référentiel définit toutes les fonctions techniques qui peuvent être réalisées par une variété de produits. Il est unique pour tous les produits que l'on souhaite comparer. Une fois défini, les composants sont alloués à des fonctions techniques. Un groupe fonctionnel est donc l'ensemble des composants alloués à une fonction technique. Lors de la modélisation du produit, toutes les fonctions techniques ne sont pas nécessairement utilisées. Un composant doit être alloué à au moins une fonction technique mais peut également appartenir à plusieurs. Inversement, une fonction technique réalisée est représentée par un groupe fonctionnel contenant au moins un composant. Les composants alloués dans un groupe fonctionnel ne sont pas obligatoirement tous liés par des liaisons mécaniques, (c.à.d. ne forment pas obligatoirement un sous-graphe du DFC). Les groupes fonctionnels sont indiqués par des zones colorées dans le DFC.

Pour la détermination des technologies, deux modèles supplémentaires sont nécessaires : la taxonomie d'un processus d'assemblage ainsi que la classification de l'information correspondant à la taxonomie. Pour la taxonomie, un processus d'assemblage est décomposé en technologie d'assemblage et attribut de liaison. Les technologies d'assemblage concernent les technologies qui sont utilisées pour réaliser le lien mécanique d'une liaison. Les attributs de liaison regroupent toutes les technologies qui sont nécessaires afin d'assurer la bonne qualité d'une liaison mécanique mais qui ne sont pas des technologies d'assemblage. Par exemple, une technologie d'assemblage peut être soudage ou assemblage boulonné. Et un attribut de liaison peut être traitement thermique ou graissage. Les attributs de liaison interviennent avant ou après la technologie d'assemblage, par exemple il faut graisser des composants avant de réaliser un assemblage boulonné. Plus en détail, pour chaque technologie d'assemblage, des opérations d'assemblage sont définies. Analogie, pour les attributs de liaison, des opérations complémentaires sont définies. Puis, au dernier niveau de détail, les paramètres discriminants et opérationnels sont définis pour chaque opération. Ils regroupent des informations telles que les degrés de liberté éliminés par l'opération, les critères comme force, déplacement, angles, etc. ainsi que des critères discriminants qui permettent d'identifier des compatibilités entre différentes opérations du même type. Un aperçu complet de la taxonomie est fourni dans Figure III.12 et toutes les informations de la classification sont accessibles en Annexe B. Un fichier sous forme Excel pour permettre de saisir les informations liées à l'assemblage de manière cohérente a été introduit. Il contient tous les éléments de la taxonomie (Figure III.14).

Les technologies d'assemblage et attributs de liaison sont ajoutées en tant qu'information supplémentaires sur les arcs du DFC. Le nouveau modèle de produit obtenu est appelé **DFC enrichi**.

Ce DFC enrichi est le point de départ pour la génération de l'architecture physico-fonctionnelle (PHARE – physical and functional architecture). Pour effectuer cette transformation, les groupes fonctionnels et leurs relations entre eux sont analysés. Dans le DFC enrichi, il existe cinq types différents de relations entre groupes fonctionnels :

- L'identité : Deux groupes fonctionnels sont identiques car ils contiennent exactement les mêmes composants ;
- L'inclusion : Un groupe fonctionnel est inclus dans un autre car l'ensemble de ses composants est un sous-ensemble de composants du groupe fonctionnel l'incluant ;
- La partition : Deux groupes fonctionnels partagent partiellement les mêmes composants ;
- Contact : Deux groupes fonctionnels sont liés par un lien mécanique, ce qui signifie qu'il existe un lien mécanique (arc dans le DFC) entre leurs composants ;
- Séparations : aucun lien existe entre deux groupes fonctionnels.

Basé sur ces cinq relations différentes, le PHARE est généré (Figure III.8). Cette représentation bascule le modèle du produit axé sur les composants et leurs liens qui est le DFC vers un nouveau modèle basé sur les relations des groupes fonctionnels. Le PHARE est en conséquence sur un niveau d'abstraction supérieur que le DFC enrichi. Les nœuds dans le graphe du PHARE représentent donc les groupes fonctionnels et les différents liens les relations entre eux. Comme indiqué dans la section précédente, les groupes fonctionnels se basent sur un référentiel de fonctions techniques qui ne change pas pour un ensemble de produits que l'on souhaite comparer. Le PHARE peut également être généré dans sa forme matricielle. Dans ce cas, chaque fonction technique est représentée par une ligne et colonne. Dans l'intersection des différentes fonctions techniques, on note les valeurs de leurs relations : 0 pour les séparations, -1 pour les contacts partants, +1 pour les contacts entrants, 2 pour les partitions (qui n'ont pas d'orientation), -3 pour les inclusions partants (relation « est inclus dans »), +3 pour les inclusions entrants (relation « inclut »), et 4 pour les identités (qui n'ont pas d'orientation). Si des fonctions techniques ne sont pas réalisées dans un produit, leur ligne et colonne respective ne contiennent que des zéros. Ces matrices du PHARE ont la même taille pour tous les produits qui sont modélisés avec le même référentiel de fonctions techniques. Le modèle du produit ne dépend donc plus des composants et il est en conséquence insensible au nombre et type de composants. De cette manière, le modèle du produit PHARE permet l'analyse et la comparaison d'une variété de produits par le biais des fonctions techniques et leurs groupes fonctionnels.

Les aspects présentés concernant l'information d'assemblage et modèle enrichi de DFC et de PHARE ont été intégrés dans un logiciel prototype développé avec Python dans le cadre de la chaire industrielle. L'avantage de cette intégration est de réaliser un traitement automatique de l'information saisie. Lors de la saisie manuelle des données d'entrée, la technologie d'assemblage est saisie en même temps que le modèle de produit. Cela signifie que, lorsqu'il s'agit de définir les relations entre les composants de la modélisation DFC, l'information sur la technologie d'assemblage et l'attribut de lien est saisie immédiatement.

En résumé, deux nouveaux modèles de produits complémentaires ont été introduits dans le Chapitre III pour répondre à la question de la recherche. Les deux sont basés sur la représentation DFC, l'un est dédié à l'analyse structurelle, l'autre à l'analyse de l'assemblage. Leur utilisation et leur interaction sont présentées dans les Chapitres IV et V. Les modèles présentés ont été testés et validés par une application industrielle sur onze différents produits mécaniques et mécatroniques complexes. Ces produits sont différents en nombre de composants (de 20 à 70 composants), le type de composant (mécanique, électronique et électrique) et le nombre de fonctions techniques réalisées (de 14 à 21). Ainsi, la variété du produit a été représentée par les choix du produit. Un extrait de ces applications est disponible dans Chapitre VI mais sous un accès restreint en raison de la confidentialité des applications industrielles.

Génération et amélioration de familles de produits (Chapter IV)

Pour la co-évolution et la co-conception du système de produit, de processus d'assemblage et d'assemblage, la génération des deux familles de produits adaptées à un système d'assemblage et des systèmes d'assemblage multiproduits pour les familles de produits est d'une grande importance. C'est l'un des défis actuels et des sujets de recherche dans l'environnement de marché instable d'aujourd'hui pour les entreprises dans le domaine de la productique. La génération de familles de produits nécessite des outils et méthodes pour analyser le portfolio de produits, en termes de similarité structurelle et d'assemblage. Cette question est abordée par l'objectif de recherche 2. Les exigences à une analyse de similarité sont les suivantes :

- Des indices de similitude sont nécessaires qui tiennent compte d'une part des architectures de produit et qui prennent également en compte la similitude des choix de technologie d'assemblage dans la conception de produit ;
- En outre, l'analyse de l'assemblage doit être sensible à la variété et donc pas Booléen (exactement le même - complètement différent).

Comparaison de la similarité structurelle – les indices S_1 et S_2

La comparaison structurelle doit être en mesure de faire face à la variété des produits. Par conséquent, il est basé sur les architectures physico-fonctionnelles (PHARE) des produits. Ce modèle de produit a été particulièrement développé pour cette raison. Pour l'analyse de similarité, les groupes fonctionnels et leurs relations sont comparés. Les deux indices de similarité structurelle sont appelés S_1 et S_2 et sont situés dans le paramètre de recherche de l'objectif 2.1.

Le calcul de S_1 et S_2 lui-même est basé sur la matrice qui représente le PHARE. Pour rappel, il représente les relations entre les groupes fonctionnels et une matrice est générée pour un produit. La matrice est définie en équation (III.2).

La représentation PHARE fournit deux points de vue différents sur la similarité des produits. D'une part, la similarité peut être évaluée en comparant les relations communes entre les groupes fonctionnels de deux produits. Cette analyse est axée sur la similarité de conception pendant en évaluant si les groupes fonctionnels réalisés sont situés de la même manière dans l'architecture de produit. Cet indice est appelé S_1 .

Similarité de l'architecture du produit : S_1 – similarité de la conception

D'autre part, la similarité peut également être évaluée en tenant compte, en plus des relations communes existantes, des relations communes absentes. L'examen de ces dernières permet d'évaluer la similarité de la complexité de conception de deux produits. Un nombre différent de relations absentes signifie que le même groupe fonctionnel a plus d'imbrications avec d'autres dans un produit que dans l'autre. Comme le nombre d'imbrications est un indicateur de complexité, un nombre différent d'imbrications signifie une complexité différente. Il convient de noter que la similarité de complexité est évaluée et qu'aucune déclaration n'est faite par l'indice de similarité sur le fait si la conception est complexe ou non. Pour une analyse de complexité, on peut se référer au couplage des sous-ensembles fonctionnels tel que décrit au Chapitre III. L'indice est appelé S_2 .

Similarité de l'architecture du produit : S_2 – similarité de la complexité

Lors de la comparaison de deux produits, une valeur de similarité S_1 et S_2 est calculée pour chaque groupe fonctionnel afin d'identifier les sous-ensembles qui sont similaires dans les deux produits. Pour résumer, le raisonnement de la démarche est décrit ensuite :

1. Génération des matrices représentant le PHARE
2. Comparaison binaire des deux matrices (pour deux produits) pondération des entrées
 - a. Identification d'éléments identiques
 - b. Identification d'éléments similaires
3. Évaluation de similitude par sous-ensemble fonctionnel

Les indices de similitude S_1 et S_2 sont couplés. Ils doivent être interprétés conjointement pour la déduction. Les deux indices peuvent être interprétés de la manière suivante :

- 100% pour S_1 et 100% pour S_2 : le groupe fonctionnel existe dans les deux produits dans une architecture de produit similaire d'une complexité similaire ;
- 0% pour S_1 et 100% pour S_2 : le groupe fonctionnel n'existe pas dans les produits examinés et n'est donc plus pris en compte ;
- 0% pour S_1 et pour $S_2 - 100%$: le groupe fonctionnel n'existe que dans l'un des deux produits examinés. Ou il est situé d'une manière complètement opposée dans l'architecture physique et fonctionnelle des produits. Dans les deux cas, il doit être gardé à l'esprit comme élément de différenciation important ;
- 0% x 100% pour les deux indices : le domaine de l'interprétation soumis à une certaine incertitude.

Pour le dernier cas, trois combinaisons de valeur différentes existent :

- S_1 élevé et S_2 élevé : les produits sont d'une architecture physico-fonctionnelle similaire et d'une complexité structurelle similaire ;
- Faible S_1 et faible S_2 : les produits ont une architecture physico-fonctionnelle avec peu de similitude et une complexité structurelle différente ;
- Faible S_1 et S_2 élevé : les produits ont une faible similarité de la conception, mais, cependant, la complexité structurelle similaire.

La combinaison de S_1 élevé et faible S_2 n'est pas possible en raison de la définition des indices. Un score S_1 élevé induit automatiquement un score S_2 élevé. Les interprétations présentées ci-dessus sont une interprétation générique des valeurs de l'indice en fonction de la façon dont elles sont calculées et de l'information définie dans le modèle PHARE. Les indices S_1 et S_2 ne tiennent compte que de l'architecture des produits fonctionnels et physiques, mais ils ne donnent aucune information sur les technologies d'assemblage utilisées. Ces connaissances supplémentaires sont nécessaires pour décider du type de système d'assemblage à sélectionner.

Comparaison des technologies d'assemblage – les indices S_3 et S_4

La comparaison d'assemblage est basée sur le DFC des produits qui a été étendu avec des informations de technologie d'assemblage. Ce modèle de produit a été développé dans le but de permettre la comparaison des technologies d'assemblage d'une variété de produits. Pour l'analyse de similarité, la technologie d'assemblage utilisée par les groupes fonctionnels est comparée. Les deux indices de comparaison de la technologie

d'assemblage sont appelés S_3 et S_4 et sont situés dans le domaine de la recherche objectif 2.2.

L'indice S_3 évalue la similarité interne à chaque groupe fonctionnel. Il considère les technologies d'assemblage utilisées dans ce groupe fonctionnel. Cela signifie que tous les liens mécaniques qui sont situés dans celui-là sont examinés. S_3 détermine ainsi la façon dont un groupe fonctionnel est réalisée. En conséquence, la similarité évaluée par S_3 est appelée similarité d'assemblage interne.

Similarité des technologies d'assemblage : S_3 - similarité de l'assemblage dans un groupe fonctionnel (interne)

L'indice S_4 évalue la similarité des technologies d'assemblage utilisées pour assembler un groupe fonctionnel avec d'autres. Cela signifie que la similarité de la technologie d'assemblage est examinée qui concerne les liens qu'un groupe fonctionnel a avec les autres. Il tient compte de toutes les technologies d'assemblage qui sont utilisées pour localiser un groupe fonctionnel, c'est-à-dire tous les arcs entrants. De cette façon, la similarité de la manière dont le groupe fonctionnel est assemblé avec l'ensemble du produit est examinée. En conséquence, la similarité évaluée par S_3 est appelée similarité d'assemblage externe.

Similarité de technologie d'assemblage : S_4 - similarité de l'assemblage du groupe fonctionnel avec d'autres (externe)

L'approche générale pour calculer la similarité des assemblages internes et externes suit cinq étapes :

1. Génération du nouveau modèle DFC étendu avec des groupes fonctionnels et des informations technologiques d'assemblage sur les arcs ;
2. Sélection des arcs à évaluer (internes pour S_3 et entrants externes pour S_4) ;
3. Génération d'une matrice technologique qui contient des informations sur la coïncidence technologie-groupe fonctionnel ;
4. Génération d'une matrice de comparaison pour la comparaison binaire de deux produits ;
5. Calcul de similarité par groupe fonctionnel.

La méthode de calcul standard consiste à appliquer le coefficient de similitude de Jaccard. Sa méthode de calcul générale est la taille de l'intersection divisée par la taille de l'union dans un ensemble d'échantillons de deux populations A et B comme indiqué dans l'équation (IV.10).

Par conséquent, le calcul standard des indices S_3 et S_4 compare les technologies d'assemblage qui sont communes aux deux produits avec le nombre global de technologies d'assemblage différentes qui sont utilisées dans les deux produits (équation IV.11). L'évaluation ne considère les technologies pour la similarité que si exactement la même technologie est utilisée. La similarité entre les technologies d'assemblage n'est pas prise en compte. Cela rend les valeurs de similitude pour le calcul standard S_3 et S_4 assez conservateur. Une extension de cette méthode standard est également introduite en utilisant une pondération afin de prendre en compte des similarités entre des technologies d'assemblage différentes (Section IV.1.2.2).

En ce qui concerne l'interprétation des valeurs de similarité, 100% indique qu'aucun changement technologique n'est nécessaire. Les modules concernés ne doivent contenir que la flexibilité nécessaire pour faire face à des valeurs de paramètres d'assemblage différentes et à des positions géométriques différentes. Les valeurs inférieures à 100 %

indiquent la nécessité d'une reconfiguration, c'est-à-dire le changement des technologies d'assemblage dans un même module. Si la valeur de similarité est trop faible, les efforts de reconfiguration seront trop élevés et la séparation du flux de production devrait être envisagée. Le seuil doit être définie spécifiquement pour chaque application industrielle.

Exploitation des indices de similarité

Dans les parties précédentes, des interprétations génériques des indicateurs de similitude S_1 à S_4 ont été présentées. Dans ce qui suit, quatre cas d'application différents sont présentés, dans lesquels les indicateurs sont utilisés pour la conception de produits, la génération et l'amélioration de la famille de produits, et les déductions du système de production. La figure IV.7 illustre les applications et leur emplacement dans le document.

La génération de familles de produits et l'analyse de la conception de produits peuvent être liées à l'amélioration de la conception de la famille de produits, car cette dernière peut être considérée comme une application supplémentaire basée sur les premiers. Trois stratégies d'analyse peuvent être déployées pour l'interprétation des résultats de l'analyse de similarité :

- L'analyse statistique peut être appliquée pour la génération de familles de produits (Figure IV.8) et l'analyse de la conception du portfolio (Table IV.5);
- L'apprentissage non-supervisé peut être appliqué à la génération de familles de produits (Figure IV.9) ;
- Et l'apprentissage supervisé peut être utilisé pour l'analyse du portfolio (Figure IV.10) et les déductions du système de production (Figure IV.11).

Enfin, une méthode itérative est développée pour l'amélioration de la similitude de conception de produit (IV.12). Cette méthode se base sur le PHARE et l'identification des disparités dans la conception de deux produits en identifiant des entrées différentes dans les matrices du PHARE. Ces disparités orientent le concepteur vers les endroits des produits qui doivent être améliorés afin d'augmenter la similarité. Ce cycle est réitéré jusqu'à ce que les valeurs de similarité sont jugées satisfaisantes.

En résumé, quatre nouveaux indices de similarité complémentaires ont été introduits pour répondre à la question de la recherche. Ils sont basés sur la représentation enrichie de DFC et le PHARE. Deux sont consacrés à l'analyse de similarité structurelle, deux autres à l'analyse de similarité de l'assemblage. Des applications orientées vers des solutions techniques ont été introduites. Pourtant, il reste de l'espace pour les travaux futurs, notamment en ce qui concerne la mise en œuvre ou la simulation du système de production pour vérifier les déductions d'applications et concernant l'ajout d'évaluations d'investissement.

Les indices de similarité et leurs applications, à part l'amélioration de la conception du produit, ont été appliqués à tous les produits modélisés du partenaire industriel. Pour rappel, il s'agit d'un ensemble de onze produits qui sont différents en nombre de composants (de 20 à 70 composants), le type de composant (mécanique, électronique et électrique), et le nombre de fonctions techniques réalisées (de 14 à 21). Pour l'amélioration de la conception du produit, deux produits sur onze ont été choisis, guidés par un problème auquel le partenaire industriel a dû faire face lors de l'industrialisation de ces produits.

Génération et comparaison des plans d'assemblage préliminaires (Chapter V)

Pour la conception des systèmes de production, les décisions prises pour la génération de séquences d'assemblage sont d'une grande importance, car elles définissent l'architecture du système d'assemblage. L'organisation des modules système autour des emplacements des composants est considérée comme l'élément clé de la conception de systèmes d'assemblage pour une variété de produits et un assemblage multiproduits. Cette nouvelle façon d'organiser le système de production est basée sur les composants qui sont situés dans les modules pour l'assemblage. Se concentrer sur ceux-ci pour la conception de l'architecture du système d'assemblage permet d'identifier les compatibilités dans le portefeuille de produits et d'organiser des modules d'assemblage autour de ces composants de localisation compatibles.

Le raisonnement classique dédié des étapes d'assemblage en considérant *un* module pour *une* opération avec *une* mise en position (MiP) pour *un* produit doit être surmontée. Les systèmes d'assemblage multiproduits reconfigurables et flexibles devraient être basés sur la question suivante : quelle séquence de MiP mutuelles des composants est optimale pour réaliser toutes les opérations d'assemblage de tous les produits considérés avec un minimum de changements ?

Pour répondre à cette question, une méthodologie pour la génération de plans d'assemblage préliminaires est présentée. Un plan d'assemblage préliminaire est considéré comme séquence de MiP des composants avec leurs séquences d'opération. L'ensemble du processus de génération est présenté dans Figure V.1. Il va jusqu'à une méthode pour comparer différents plans d'assemblage préliminaires. Comme indiqué, la sélection finale des plans d'assemblage (par l'évaluation, la simulation, l'estimation des investissements, etc.) n'est pas décrite dans le présent document. Toutes les étapes nécessaires à la génération et à la comparaison des plans d'assemblage préliminaires sont décrites étape par étape dans les sections suivantes.

Expression des contraintes d'antériorité par opérateurs logiques

Les contraintes de préséance, telles qu'elles sont présentées ci-après, dressent la liste des liens mécaniques qui doivent être réalisés avant les autres. Les expressions logiques et les connecteurs sont utilisés pour définir les relations de préséance. Les opérateurs d'occurrence sont introduits dans Table V.1. Les combinaisons de ces opérateurs sont utilisées pour exprimer des contraintes de préséance. L'apport des contraintes de préséance est exprimé dans un tableau représentant tous les liens mécaniques du produit. Ce tableau peut être dérivé du modèle DFC enrichi (voir le chapitre III pour les descriptions du modèle). Chaque ligne et colonne représente un composant.

À l'état initial, le tableau ne contient que des entrées égales à un si un composant est lié à un autre avec un arc sortant. Toutes les autres entrées sont égales à zéro. Chaque entrée étant égale à un représente un lien mécanique entre deux composants. Lors de l'entrée des contraintes d'antériorité, successivement les entrées égales à un sont remplacées par une combinaison d'opérateurs d'antériorité comme illustré dans Table V.1. Concernant les contraintes d'antériorités, on distingue entre deux types :

- Contraintes d'antériorité intrinsèques : ces contraintes peuvent être déduites du DFC enrichi avec des patrons (identification des sous-graphes, Figure V.5-V.8) ;

- Contraintes d'antériorité extrinsèques : ces contraintes regroupent toutes les autres contraintes qui doivent être saisies manuellement.

En général, les contraintes d'accessibilité et de suite d'opérations sont les plus importantes. En fonction des cas, des contraintes supplémentaires (poids, valeur ajoutée, ...) peuvent être ajoutées.

Identification des candidats pour mise en position (MiP)

Après l'identification des contraintes d'antériorité, la prochaine étape vers la définition des séquences d'assemblage est l'identification des composants qui sont candidats MiP. La problématique industrielle est de savoir comment définir les séquences d'assemblage et comment concevoir une chaîne d'assemblage multiproduits pour les variétés de produits. Dans ce contexte, l'identification des candidats MiP est un élément clé pour la génération de séquences d'assemblage, car ils sont considérés comme le facilitateur (ou élément discriminant) pour l'assemblage multiproduits. Cela fait de ces candidats MiP un élément important pour l'application des stratégies de séquence d'assemblage.

L'hypothèse est qu'un candidat MiP doit être situé soit au début, soit à la fin d'une chaîne de composants dans le DFC enrichi. Cela signifie que les composants étant au début ou à la fin d'une séquence d'assemblage sont censés d'être candidats pour le positionnement ; cela lors du processus d'assemblage de ses composants liés. Les séquences d'assemblage décrivent l'achèvement des liaisons mécaniques. Ainsi, le DFC enrichi, en affichant tous les liens mécaniques, contient implicitement leurs séquences.

Le DFC enrichi est donc utilisé pour identifier les candidats possibles pour la mise en position au cours du processus d'assemblage. L'identification utilise la théorie des source et puits, modifiée pour l'application actuelle adaptée au modèle DFC enrichi. Les composants ne possédant aucun arc entrant sont appelés sources, et les composants n'ayant aucun arc sortant sont appelés puits. La recherche des candidats MiP est effectuée par groupe fonctionnel (Figures V.11 and V.12). A partir de l'identification des sources et puits dans les groupes fonctionnels, les candidats MiP sont identifiés en utilisant les critères suivants :

1. Chaque source est un candidat MiP potentiel ;
2. Chaque puits est un candidat MiP potentiel ;
3. Chaque composant lié à une source ou un puits avec un lien éliminant six degrés de liberté est un candidat MiP potentiel ;
4. En outre de ses composants, chaque composant ayant un beaucoup plus grand nombre d'arcs sortants que arcs entrants est un candidat MiP potentiel.

La MiP doit être soutenue par les surfaces disponibles des composants identifiés. Les surfaces disponibles sont les surfaces qui ne seront pas utilisées pour y assembler des composants pendant le processus d'assemblage du produit.

Afin de pouvoir identifier les groupes fonctionnels pour la recherche des candidats MiP, la représentation PHARE est contractée. Pour cela, toutes les groupes fonctionnels ayant des relations d'identité ou d'inclusion sont fusionnés. Le PHARE contracté, orienté assemblage, affiche seulement les groupes fonctionnels ayant les relations partition, contact ou séparation. Il ne contient plus d'information redondante et affiche les différents groupes fonctionnels qui interviennent dans l'assemblage.

Dans les applications pratiques, les candidats MiP sont ajoutés au modèle générique pour la saisie d'informations sur l'assemblage (fichier Excel mentionné au préalable).

Un fichier est utilisé par groupe fonctionnel. Les candidats MiP qui ont été identifiés sont intégrés dans ce fichier, illustré dans Figure V.18. Il contient l'information sur la question de savoir si un lien mécanique peut être réalisé en utilisant un candidat MiP ou non. Pour déterminer si un candidat MiP est adapté à la réalisation d'un lien mécanique, trois critères doivent être analysés : « accessibilité et orientation », « degré de liberté du lien mécanique » et « force ». Toutes les connexions d'un candidat MiP sont réalisables si elles ne sont pas contradictoires avec ces critères.

Cependant, les candidats identifiés de cette façon sont théoriques et peuvent ne pas être idéaux dans un environnement réel. L'objectif est d'identifier le nombre minimum de candidats à la localisation pour une assemblée de produits. Idéalement, il existe un candidat MiP qui permet la réalisation de toutes les étapes de l'assemblage, c'est-à-dire un candidat universel à la mise en position pour le produit entier. Celui-ci peut être appelé une MiP idéale. Après l'identification de tous les candidats, ils doivent être divisés en candidats possibles pour un examen plus approfondi ou des candidats impossibles qui devraient être écartés. Cette évaluation doit être effectuée par un expert industriel.

Fusion des contraintes d'antériorité avec les candidats MiP

La fusion des contraintes d'antériorité avec l'information des candidats MiP se traduit par un graphe d'antériorité-MiP, illustré dans la Figure V.24. Son processus de génération est illustré dans la Figure V.25. Le graphe d'antériorité-MiP est défini avec les nœuds étant les liens mécaniques avec leurs opérations et les arcs étant l'information d'antériorité. Si deux opérations sont réalisées en même temps, elles partagent le même nœud. La conception de la représentation graphique elle-même est compatible avec la représentation du DFC enrichi.

Les opérations complémentaires sont rattachées à leurs opérations d'assemblage par un cadre rectangulaire. Il rassemble toutes les opérations effectuées sur le même lien mécanique. Trois informations d'antériorité différentes sont affichées : pas d'antériorité (pas d'arc), antériorité standard (arc avec une seule flèche) et antériorité immédiate (arc à double flèche). Les sous-assemblages indépendants en termes d'antériorité sont représentés par des sous-graphes non connectés. Ainsi, un assemblage de produits peut être représenté par plusieurs sous-graphes non connectés si ses sous-ensembles ne sont pas liés par des contraintes d'antériorité. Les possibilités de localisation sont représentées par des zones couvrant les nœuds du graphique de préséance. L'attribution des opérations à la localisation des candidats s'appelle module de localisation. Chaque zone représente un candidat de localisation.

Un cas particulier se produit, lorsqu'un nœud comprenant deux opérations parallèles ou plus est affectée à des candidats MiP différents (comme illustré avec le candidat local dans la Figure V.24). Dans ce cas, il existe deux possibilités : soit l'un des candidats MiP est utilisé pour toutes les opérations si l'assemblage le permet. Soit les deux opérations sont effectuées en utilisant les deux candidats en même temps car il s'agit des opérations parallèles.

Les zones des candidats MiP peuvent également être indépendants, se chevaucher ou s'inclure. Les chevauchements signifient que différentes possibilités de localisation existent. On peut choisir un seul des candidats MiP ou en utiliser une combinaison.

Génération des plans d'assemblage préliminaires

La première étape de la génération des plans d'assemblage préliminaires est l'application de stratégies de mise en position. Ce choix détermine la structure macroscopique du système de production. Deux philosophies différentes sont identifiées et présentées dans ce qui suit :

1. La maximisation des opérations qui sont réalisables par (une) MiP avec un minimum de modules reconfigurables (opérations communes, utilisation mutuelle d'installations et faible nombre de module) (Figures V.28 et V.29) ;
2. La division du système d'assemblage en fonction de différentes MiP dans des modules distincts avec débit élevé (faible mutualité d'opérations et nombre élevé de modules) (Figures V.30 et V.31).

Ces philosophies correspondent aux défis relevés par chaire industrielle, en particulier la question des systèmes flexibles et modulaires par rapport aux systèmes spécifiques et dédiés à haute performance. Les schémas des deux stratégies sont illustrés dans Figure V.27. Dans stratégie (1), un module rassemble plus d'opérations, et les opérations ou les candidats de localisation sont mobiles (flexibilité du mouvement) afin de réaliser toutes les opérations sur le même candidat de localisation. Stratégie (2) a des modules plus différents avec des emplacements statiques et rassemble moins d'opérations qui permet l'adaptation des modules aux opérations et nécessite pas ou moins de flexibilité cinématique. Un candidat MiP choisi pour un ensemble d'opérations est appelé un module MiP.

Dans les assemblages complexes, il peut arriver qu'il existe un module de MiP indépendant qui utilise le même candidat MiP que plusieurs modules intégrés dans une séquence d'antériorités. Dans ce cas, le module indépendant peut être mutualisé avec les modules intégrés. La question est de savoir où il convient de l'intégrer. Table V.2 fournit un exemple de critères de prise de décision qui peuvent être utilisés pour répondre à cette question. Selon l'application industrielle, l'utilisation de tous les critères en même temps pourrait être contradictoire. Ou, comme la liste n'est pas censée être exhaustive, des critères supplémentaires pourraient être nécessaires.

Après la génération préliminaire d'un ensemble de séquences de modules MiP (ou une seule séquence, selon la stratégie et les critères choisis), les opérations d'assemblage doivent également être ordonnancées. L'ordonnancement des modules MiP donne une séquence macroscopique, mais entre chaque module, s'il y a plus qu'une opération, les opérations doivent également être ordonnées pour déterminer le plan d'assemblage final. Soit des critères sont appliqués pour cet ordonnancement, soit toutes les séquences possibles sont générées pour avoir un espace de solution illimité. En ce qui concerne les critères d'ordonnancement d'opérations, une vue globale est fournie dans Table V.3.

Analogue aux critères de regroupement MiP, la liste ne prétend pas d'être exhaustive et peut varier selon les cas d'application. Et l'application de tous les critères en même temps est susceptible de donner des résultats contradictoires. Il faut choisir les plus pertinents et définir des priorités pour éviter cela.

Les plans d'assemblage préliminaires obtenus se constituent finalement des éléments suivant : une séquence de modules MiP, des opérations ordonnées dans les modules MiP, ainsi que l'information complémentaire des opérations telle que définie dans la taxinomie.

Comparaison des plans d'assemblage préliminaires

Pour la comparaison de plan d'assemblage préliminaires, une information est essentielle : la similarité des candidats MiP dans les deux produits examinés. Pour assurer la compatibilité d'un module MiP pour un assemblage multiproduits, il faut s'assurer que les candidats correspondants ont une forme et une géométrie correspondantes. Pour cela, les similarités doivent être examinées dans un premier temps et une liste de candidats MiP similaires doit être dressée. Il est recommandé de constituer progressivement un fichier où ces informations sont stockées.

Pour la comparaison des plans d'assemblage, trois indicateurs, basés sur une analyse LCS/SCS¹ sont introduits :

- Longueur LCS par rapport à la longueur de la séquence initiale la plus courte ;
- Longueur SCS par rapport à la longueur de la plus longue séquence initiale ;
- Nombre de caractères dans le LCS par rapport au nombre de caractères différents utilisés dans l'ensemble (similitude de Jaccard).

Le premier indicateur donne une idée si un produit peut être réalisé entièrement sur le la plus courte séquence d'assemblage. Cela signifie que des unités supplémentaires sont nécessaires pour les autres produits. Le deuxième indicateur donne une idée si la plus longue séquence d'assemblage d'un produit englobe aussi les autres. En termes de système d'assemblage, cela signifie que la ligne de production d'un produit est capable de réaliser tous les produits, mais certaines unités ne sont pas entièrement chargées. Enfin, la valeur du troisième indicateur évalue la mutualité des unités d'assemblage. S'il est élevé, cela signifie que le nombre d'opérations utilisées dans la partie commune est proche du nombre total d'opérations utilisées, ce qui indique une grande mutualité et de faibles unités inactives. Pour les valeurs basses, vice-versa.

Afin de pouvoir comparer les plans d'assemblage préliminaires, pour chaque étape, le triplet d'information MiP, opération et orientation est analysé. La séquence de ces triplets forme la signature du plans d'assemblage. En comparant deux plans d'assemblage, les séquences de triplets sont comparées. L'information dans les triplets se situe sur trois niveaux différents, ce qui a un impact différent sur le système d'assemblage :

- MiP : niveau de structure du système d'assemblage (unités identiques ou différentes)
- Opération d'assemblage : niveau de l'unité d'assemblage (reconfigurable ou mono-opérationnel)
- Orientation : niveau d'opération d'assemblage (flexible ou rigide)

Par conséquent, en choisissant de comparer toutes les informations ou seulement une partie de celle-ci, on peut déterminer la granularité de la comparaison. En général, il existe trois options allant de la macro-comparaison à la micro-comparaison :

- Option 1 : localisation du candidat uniquement
- Option 2 : localisation du candidat et opération
- Option 3 : localisation du candidat, de l'opération et de l'orientation

¹ Pour rappel : SCS = Shortest common supersequence (séquence englobante la plus courte)
LCS = Longest common subsequence (séquence commune la plus longue)

Figure V.39 montre un plan d'assemblage préliminaire traduit en séquence de triplets. Comme mentionné, ceux-ci contiennent l'information de la MiP, de l'opération et de l'orientation opérationnelle pour chacune des étapes de l'assemblage. Les plans d'assemblage préliminaires sont basés sur les séquences des modules MiP. Ceux-ci sont conservés dans la représentation de la signature et leurs interconnexions sont montrées par des coupures dans celle-ci. Cette représentation permet finalement de comparer deux plans d'assemblage préliminaires ou plus.

L'étape de comparaison est dédiée à générer les séquences d'entrée pour les calculs de LCS et SCS. Les séquences d'entrée sont déterminées en comparant les signatures des plans d'assemblage triplet par triplet concernant l'option choisie. En ce qui concerne les modules MiP, l'information de compatibilité, définie au préalable, doit être utilisée. Une chaîne de caractères est construite en comparant les triplets : si deux triplets sont identiques en ce qui concerne les critères choisis, le même caractère leur est assigné. Si ce n'est pas le cas, différents caractères sont attribués. Le processus est illustré dans Figure V.40.

Le résultat de cette comparaison est une chaîne de caractères pour chaque signature de plan d'assemblage. Comme les plans d'assemblage préliminaires sont basés sur les séquences de modules MiP, l'analyse de LCS et SCS est basée sur elles aussi. Les séquences d'entrée pour les calculs LCS et SCS sont divisées selon leurs séquences de module MiP. Les modules MiP compatibles sont connus. Les séquences de ces modules compatibles sont analysées avec LCS et SCS. S'il existe des séquences d'un produit qui n'ont pas de contrepartie dans d'autres produits, en raison de l'absence de candidats compatibles de localisation, ceux-ci ne sont pas disponibles pour la comparaison de similarité. Une illustration est donnée à travers les exemples dans Chapitre V.

Trois cas d'application possibles pour l'analyse LCS/SCS existent. Le premier est la comparaison d'un plan d'assemblage existant (d'un produit existant déjà en production) à un ensemble de plans d'assemblage possibles pour un nouveau produit afin de déterminer lequel des plans d'assemblage du nouveau produit correspond le mieux à celui du produit existant. Le deuxième cas est la comparaison des ensembles de plans d'assemblage les uns aux autres afin de déterminer quelle combinaison de plans d'assemblage est la meilleure. Le troisième cas est l'analyse parallèle des plans d'assemblage de plusieurs produits lors de la détermination des plans d'assemblage préliminaires dans une approche d'optimisation pour générer une solution optimale pour plusieurs produits.

Dans cette section, des modèles et des approches ont été introduits pour accomplir la dernière étape de la partie de modélisation de produit à la conception du système d'assemblage. Le point final du travail est la génération et la comparaison des plans d'assemblage préliminaires qui contiennent des séquences de modules MiP avec leurs opérations d'assemblage allouées ainsi que leurs informations complémentaires. La prise de décision, comment choisir un plan d'assemblage parmi tous ceux qui ont été générés et qui sont techniquement possibles, n'a pas été abordé dans ces travaux. L'approche a été testée sur trois produits mécaniques complexes de notre partenaire industriel (jusqu'à 50 composants et 20 fonctions techniques différentes).

A noter : le sixième chapitre « Etude de cas » est soumis à la confidentialité et, en conséquence, n'est pas détaillé ici.

Conclusion et perspectives (Chapter VII)

L'objectif de cette recherche est de proposer une contribution à la co-conception du produit, des procédés et du système de production dans le cadre d'un processus d'assemblage reconfigurable. Elle a été réalisée en tant que recherche appliquée en étroite coopération avec le partenaire industriel afin de s'assurer que les solutions proposées répondent aux besoins industriels et s'appliquent dans le contexte industriel. Pour rappel, la question de la recherche mondiale qui a été définie au début de ce document comme cadre pour les travaux de recherche est

Comment analyser, mesurer et augmenter l'agilité d'un système de production ?

Dans ce domaine de recherche, le sujet de recherche spécifique a été défini par la question scientifique suivante :

Comment concevoir un système de production reconfigurable compte tenu des familles de produits et de leur assemblage en abordant les aspects de la coévolution ?

À partir de ces questions clés, un ensemble de trois objectifs de recherche a été défini, structurant la conclusion.

Conclusion

Pour répondre aux questions de recherche de l'objectif 1, deux nouvelles représentations de produits ont été introduites : le DFC enrichi et le modèle PHARE. Avec ces deux modèles de produits, les exigences définies pour l'objectif 1 sont satisfaites : les modèles permettent l'analyse et la comparaison d'une variété de produits en termes d'architecture de produits et de technologies d'assemblage. Les limitations de l'application sont données par le référentiel de fonction technique qui doit être commun pour tous les produits examinés. Il ne prend pas en charge la comparaison de produits complètement différents, en ce qui concerne la fonction qu'ils exécutent, qui peuvent avoir les mêmes technologies d'assemblage. En outre, les connaissances proposées en matière de technologie d'assemblage ne sont pas exhaustives, car elles sont orientées vers les cas d'utilisation industrielle et peuvent être complétées.

Pour répondre aux questions de recherche d'objectif 2, quatre nouveaux indices de similarité ont été définis. Deux sont basés sur la représentation PHARE et évaluent la conception fonctionnelle et architecturale ainsi que la similarité de complexité. Les deux autres sont définis au niveau du DFC enrichi et évaluent la similarité de la technologie d'assemblage dans les groupes fonctionnels ainsi que la similarité des technologies utilisées pour les assembler. L'approche de l'indice de similarité dépend fortement de son application industrielle. Cela signifie que les indices de similarité ont un périmètre local : les valeurs avec leurs déductions sont liées aux produits et aux processus de production de l'entreprise partenaire industrielle. Lors de l'application à de nouveaux cas différents, une phase d'étalonnage est nécessaire, pour définir les domaines de valeur, les seuils et leur interprétation. Les interprétations des valeurs de similarité avec leurs seuils d'appartenance ne sont pas destinées à définir des énoncés valables à l'échelle globale. Cependant, la méthodologie et ses applications sont applicables à l'échelle globale.

Pour répondre aux défis liés à l'objectif 3, une nouvelle vue d'un système de production est proposée : au lieu d'avoir des modules par étapes et opération d'assemblage, une vue sur les composants utilisés pour la mise en position (MiP) est proposée. Cette mise au point permet de définir des modules MiP, c'est-à-dire des modules qui rassemblent des opérations autour du composant dont le positionnement dans le module permet leur réalisation. L'identification de ces modules MiP permet l'application de différentes stratégies pour l'architecture du système et la génération de lignes d'assemblage multiproduits en mettant en position des composants compatibles. La reconfigurabilité est induite par le fait d'avoir plusieurs opérations possibles autour d'une MiP.

Pour générer les plans d'assemblage préliminaires selon les plans d'assemblage préliminaires, trois aspects différents ont été abordés : l'identification des contraintes d'antériorité, l'identification des groupes fonctionnels pertinents pour l'assemblage et l'identification des candidats MiP. Sur la base de ces informations, une nouvelle vue du produit, le graphe MiP-antériorité est généré, qui est utilisé pour générer des ensembles de plans d'assemblage préliminaires réalisables. L'espace de solution peut être restreint en appliquant des contraintes d'ordonnancement.

Enfin, pour permettre la comparaison des plans d'assemblage préliminaires pour déterminer les ligne d'assemblage multiproduits, une approche a été proposée qui permet la génération de chaînes de caractères représentant des séquences d'assemblage à comparer avec les méthodes LCS/SCS. Cette comparaison permet de déterminer les parties communes et différentes dans les séquences d'assemblage.

L'approche proposée permet la génération et la comparaison des plans d'assemblage préliminaires. Elle a été testée tout au long d'une application sur trois produits mécaniques complexes du partenaire industriel. Le nouveau raisonnement utilisant les MiP et leurs modules conduit au développement d'un nouveau type de module d'assemblage et de processus d'assemblage dans l'entreprise du partenaire industriel, qui est censé répondre à leurs besoins de reconfigurabilité.

L'approche elle-même repose fortement sur la définition des modèles de base (DFC enrichi et PHARE) ce qui signifie que la génération de plans d'assemblage préliminaires est sensible à la cohérence de la modélisation du produit. De plus, lors de l'identification des candidats à la localisation et des contraintes de préséance, leur entrée et leur validation (partielles) par l'intermédiaire d'un opérateur sont utilisées. Différents opérateurs ayant une vision/vue différente de l'assemblage peuvent également introduire des incohérences et les opérateurs peuvent ajouter des contraintes non essentielles en raison de leurs préférences personnelles. Ces facteurs peuvent avoir un impact sur les solutions générées ainsi que sur la fiabilité de la comparaison. Comme toutes ces applications s'appuient sur DFC enrichi et PHARE, leur limite d'utilisation est définie par le référentiel des fonctions techniques, comme mentionné dans les sections précédentes.

Perspectives et futurs travaux

Les travaux de recherche présentés, s'adressant au produit, processus et au système de production, couvrent de multiples aspects de recherche. Des perspectives de développement existent pour chacun d'eux. Ensuite, pour chacun des modèles et des approches qui ont été présentés dans ce travail, leurs limites sont soulignées dans ce qui suit et les perspectives pour d'autres travaux sont affichées.

L'approche PHARE est limitée par un référentiel de fonctions techniques. Pour les études de cas industrielles, il a été appliqué à une grande variété de produits, prouvant son applicabilité à l'analyse des variétés de produits. Cependant, en comparant les variétés de produits appartenant à différentes catégories de produits, le référentiel technique doit nécessairement devenir plus générique. Cette abstraction conduit à une perte de sens technique pour les fonctions techniques et donc aussi à une perte du sens technique des groupes fonctionnels dans l'approche PHARE. **De futurs travaux sur cette question devraient examiner les limites des applications référentielles de fonction technique.**

En ce qui concerne le **DFC enrichi**, dans l'approche proposée, il couvre l'information sur les liens mécaniques, la localisation relative des composants, les degrés de liberté éliminés, les technologies d'assemblage usagés et les attributs de liaison. **D'autres informations pourraient être ajoutées à ce stade qui peuvent soutenir la prise de décision pendant la génération de séquences d'assemblage**, reflétant les critères proposés.

Enfin, **l'analyse et la comparaison de l'assemblage** basées sur les deux modèles ont été appliquées avec succès. Il a été révélé que le sens et la génération des indices S_1 et S_2 n'est pas facilement compréhensible pour les utilisateurs non formés sans explications en profondeur. Cela peut être un obstacle au déploiement rapide de ces indices. En ce qui concerne le calcul de S_1 et S_2 , toutes les FSA et toutes les relations sont considérées de manière égale. **Un raffinement peut être fait en pondant les relations ou en pondant certains sous-ensembles fonctionnels qui sont considérés comme plus importants que les autres.**

Tout au long de l'approche PHARE et de ses applications, **les connaissances de processus d'assemblage** sont nécessaires et utilisées. Dans le cadre de ce travail de recherche, une taxonomie a été proposée pour encadrer ces connaissances. Pour chacune de ses catégories, des éléments (opérations, types de paramètres, ...) ont été définis. Toutes ces informations ont été connectées en définissant les liens entre les éléments. Toutefois, il n'a pas été formalisé dans une expression spécifique (p. ex. logique de premier ordre). Ainsi, d'autres travaux peuvent être la **traduction de règles et de contraintes appartenant aux éléments des catégories de taxonomie en un solveur CSP² pour permettre leur mise en œuvre.**

Pour la **gestion de la variété de produits**, la génération de produits familiaux et l'amélioration de la similarité de conception de produit, plusieurs applications ont été présentées, toutes basées sur les indices S_1 à S_4 . Trois approches (apprentissage supervisé, apprentissage sans surveillance et analyse statistique) ont été proposées pour la génération de familles de produit ainsi que l'analyse et la gestion de la variété. En ce qui concerne les approches d'apprentissage supervisé, leur applicabilité globale a été démontrée, mais des domaines d'entrée exacts doivent encore être déterminés en coopération avec le partenaire industriel. En outre, les déductions possibles doivent être vérifiées par des études de cas supplémentaires. En ce qui concerne l'approche de clustering, **des critères supplémentaires que les indices S_1 à S_4 pourraient être ajoutés.** Par cela, d'autres critères que la conception et la technologie d'assemblage peuvent être considérés.

Enfin, en ce qui concerne l'amélioration de la similarité de conception de produit, la méthodologie proposée montre des différences dans la conception du produit et les choix de technologies d'assemblage, et propose des possibilités d'amélioration (un

² CSP = Constraint satisfaction problem (problème de satisfaction de contraintes)

espace de solutions techniques). Cependant, aucune aide à la décision n'est fournie, car la décision est laissée libre à l'opérateur. Afin de combler cet écart, pour chaque boucle proposant des modifications, **une analyse DFA peut être couplée. De cette façon, les aspects des coûts et des efforts d'assemblage seront intégrés à la boucle d'amélioration** et fournissent une aide à la prise de décision.

Le troisième aspect du travail de recherche concerne l'intégration des processus produits pour la génération de plans d'assemblage préliminaires. Il commence par l'identification des **contraintes d'antériorité**. Des patrons de sous-graphes ont été définis qui permettent la reconnaissance automatique partielle des antériorités dans le DFC enrichi. Ces quatre modèles sont généralement applicables. Toutefois, il se peut que la liste ne soit pas exhaustive ou que des modèles supplémentaires puissent être trouvés spécifiques aux applications industrielles. **Par conséquent, des travaux supplémentaires peuvent être effectués sur la définition des patrons.**

En ce qui concerne **l'identification des candidats MiP**, la méthode telle qu'elle a été développée au cours des travaux de recherche résulte en un ensemble de candidats MiP potentiels. Analogie à l'amélioration de la similarité du produit, aucune décision n'est préconisée, lesquels entre eux sont les plus performants et, si une stratégie MiP est choisie, laquelle est la meilleure en termes de retour de l'investissement, de cadence, etc. Cela signifie que **les résultats de l'identification des candidats MiP doivent être soumis à une étape d'évaluation pour déterminer lesquels choisir**. On peut en dire autant de la génération et de la comparaison des plans d'assemblage préliminaires.

L'approche de **comparaison des plans d'assemblage** préliminaires avec l'application des méthodes LCS et SCS permet d'identifier quelles parties des séquences d'assemblage sont courantes, similaires ou différentes. Ces informations aident à définir l'architecture globale du système d'assemblage. Toutefois, lorsqu'il s'agit de la mise en œuvre détaillée, de la prise de décision quelle solution technologique à choisir pour chaque module ainsi que la façon de les concevoir, aucun support décisionnel n'est apporté. **De futurs travaux devraient intégrer l'information à l'approche qui appuie la prise de décision**. Il s'agit aussi d'examiner la possibilité d'une application conjointe de méthodes d'optimisation pendant les phases de génération des plans d'assemblage afin de générer un seul résultat optimisé au lieu d'un espace de solutions. **Une approche axée sur la recherche opérationnelle** utilisant la programmation linéaire, et ayant comme fonctions objectifs des critères comme coût ou cadence, **pourrait être combinée avec l'approche de génération de séquences d'assemblage**. L'idée est d'évaluer les séquences au cours de leur génération d'une manière itérative. Également, **l'approche peut être orientée vers le couplage de la génération de plans d'assemblage avec des approches de simulation** et des outils, de sorte que la prise de décision peut être basée sur la simulation de différents scénarios.

La conclusion et les perspectives montrent que l'approche développée comporte plusieurs points d'amarrage où elle peut être complétée ou étendue avec des méthodes existantes. En outre, bien que les méthodes, outils et modèles présentés aient été soigneusement testés avec des études de cas industrielles, il reste de potentiel d'affinage. Par conséquent, les éléments validés de ce travail de recherche représentent en même temps plusieurs points de départ différents pour d'autres travaux de recherche couvrant des aspects de la conception de produits, en passant par l'intégration des processus, jusqu'à la conception de l'architecture du système de production.

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About this document

Structure of the manuscript

In the beginning of each chapter, the content of the chapter is summarised in a separated paragraph, added in a box separated from the text. This summary gives a short glance of the chapter, revealing its most important contributions. It represents an element a part from the information flow of the document

Inserted to the body of the manuscript, beside the text itself, definitions and illustrative examples are used to underline and explain specific points. These elements are highlighted to differ from the text body.

Definitions are introduced in grey boxes. They are positioned in the text, where they occur the first time. All definitions are numbered and can be consulted in the glossary of definitions.

Illustrations of introduced models, methods and applications are described in the text body and highlighted by yellow boxes. For these illustrations, a small educative example has been chosen which is not issue to an industrial application. Industrial use cases and a complete industrial case study are furnished in the dedicated Appendix F. As it contains sensitive industrial information, this appendix is confidential. The examples are enumerated and a register is added in the index of tables figures and examples.

The notation of different referenced elements (figures, tables, equations, definitions...) are all starting with the chapter number and are numbered in increasing order throughout a chapter.

References are cited conform to the Harvard Author-Date citation style. The in-text citations are put into square brackets to distinguish between parentheses and citations. Picture references which are not taken out of academic references are indicated separately to the bibliography in a separate section. The same about web references.

Mathematical notations

The equations used in the document are all numbered. For matrix notation, the following convention is used:

- Matrices are indicated by bold capital letters (e.g. \mathbf{P});
- The entries of the matrices are indicated with the same letter as the matrix, in lower-case writing (e.g. p for the entries of \mathbf{P});
- The entries are indicated with indices in increasing order starting with the index i (e.g. p_{ij} for the entries of \mathbf{P}_1 , p_{kl} for the entries of \mathbf{P}_2)

Glossary

Glossary of Abbreviations

BOM	Bill of Materials
CAPP	Computer-Aided Process Planning
DFA	Design for Assembly
DFC	Datum Flow Chain
DIN	Deutsches Institut für Normung (German standardisation organisation)
DOF	Degrees of Freedom
DSM	Design Structure Matrix
FBS	Function-Behaviour-Structure
GT	Group Technology
LCFC	Laboratoire de Conception, Fabrication et Commande (Laboratory of Design, Manufacturing and Control)
LCS	Longest Common Subsequence
PCA	Principle Component Analysis
PF	Product Family
PHARE	Physical and Functional Architecture
POIM	Part Operation Incidence Matrix
PPS	Product-Process-Production System
RAS	Reconfigurable Assembly System
RMS	Reconfigurable Manufacturing System
SCS	Shortest Common Super-sequence (or Super-string)
SVM	Support Vector Machine
tkPF	thyssenkrupp Presta France
UIMM	Union des Industries et Métiers de la Métallurgie (Union of Metalworking Industries)
VDI	Verband Deutscher Ingenieure (Association of German Engineers, organisation publishing recommendations on engineering practises)

Glossary of Definitions

I.1	Flexibility	Flexibility is the intrinsic capacity of an element of the production system (e.g. workstation, module, cell, ...) to compensate external changes without modification.	p.19
I.2	Reconfigurability	Reconfigurability is the technical ability of an element of the production system (e.g. workstation, module, cell, ...) to be adaptable with modifications for external changes in production.	p.20
I.3	Agility	Agility is the technical ability of a production system to adapt to external changes. These changes may be variations in demand or product mix. It represents the global potential of the production system including its reconfigurability and flexibility capacities.	p.20
II.1	Product Family	A product family is “a set of similar products [i.e. assemblies] that share common technology platforms but have specific functionality/features to address a set of market segmentations and meet particular customer requirements.” [Zhang, Qin et al. 2019, p. 3].	p.41
II.2	Precedence Constraints	Precedence constraints “are the main links between the product domain and system domain [...]. [They] establish each product assembly sequence and determine the geometric and technological validity of a certain sequence of assembly processes.” [AlGeddawy and ElMaraghy 2010, p.5298]	p.48
II.3	Positioning/Locating	Positioning (synonym: locating) aims to remove degrees of freedom of a part in order to locate it in the three-dimensional space and in relation to other parts and to assure a needed orientation towards the assembly or manufacturing operation tool.	p.50
II.4	Clamping	Clamping has the aim to maintain a part at its location respective to any force applied by manufacturing or assembly processes.	p.50
II.5	Fixture	Fixture is called the technical element which realises locating and clamping, i.e. which ensures the location, orientation and stability of a work piece during manufacturing and assembly. It secures it against process forces.	p.50
II.6	Fixturing	Fixturing is an englobing term which describes the use of fixtures in order to achieve locating and clamping strategies. Thus it refers to the whole area from locating and clamping strategies to their technical realisation. Work holding can be used as synonym to fixturing.	p.50

III.1	Technical Function	A technical function is a mechanism of the product that must satisfy its technical requirements. It is the translation of customer needs to design parameters. If a technical function is realised it contains at least one component. The components realising the same technical function do not need to have mechanical links between them.	p.60
III.2	Functional Subassembly (FSA)	If a technical function is realised, it contains at least one component. The combination of technical function and components is called functional subassembly (FSA). The components in one FSA do not need to have mechanical links between them.	p.61
III.3	Physical and functional architecture (PHARE)	The PHARE is a hybrid product model. It is based on the relations of the product FSA between each other. These relations describe in an abstract way the product structure. It furnishes at the same time a functional and physical view of the product structure.	p.62
III.4	Assembly Operation	An assembly operation is an operation which realises a mechanical link. One assembly operation is used to realise one mechanical link. The same type of assembly operation can be used throughout an assembly to realise different mechanical links. An assembly operation is defined throughout its associated assembly parameters.	p.68
III.5	Complementary Operation	A complementary operation is an operation which realises a mechanical link. One or more complementary operations may be used around one mechanical link. The same type of complementary operation can be used throughout an assembly. Complementary operations are associated to the assembly operation of its according mechanical link by precedence information (before or after assembly operation). A complementary operation is defined throughout its associated assembly parameters.	p.68
III.6	Assembly Technology and Link Attribute	<p>Assembly technology is a term gathering assembly operations. It is a more generic granularity level which permits to choose later on the detailed operation. For example: technology = welding; operation = ultrasonic welding.</p> <p>The same is for link attribute. It gathers complementary operations. For example: link attribute = control; complementary operation = control component presence.</p>	p.69
III.7	Discriminant Parameter	Discriminant parameters define crucial criteria of an assembly operation in regard if this operation can be regrouped with others. They represent boundary values which have to be respected by	p.69

			other operations when regrouping. Discriminant parameters determine therefore if an operation can be regrouped with another one.	
III.8	Assembly Parameter	Operation	The operation parameter are all parameters which have to be set and/or monitored to ensure that the assembly operation is done well. Operation parameters can be discriminant parameters at the same time.	p.69
V.1	Intrinsic constraints	precedence	Intrinsic precedence constraints are precedence constraints which can be derived out of the enriched DFC model by combining information about assembly technology with patterns of DFC subgraphs. The intrinsic precedence constraints can be deduced automatically. They represent precedence constraint due to positioning and assembly technology constraints.	p.113
V.2	Extrinsic constraints	precedence	Extrinsic precedence constraints are all precedence constraints which cannot be derived automatically out of the enriched DFC model. They are extrinsic to the product model.	p.116
V.3	Locating candidate		A locating candidate is a component of the product or one of its subassemblies which can be a base part for other assemblies. That means a locating candidate is a component which is at the beginning or the end of a sequence of mechanical links and these can be realised by putting into position the locating candidate.	p.117
V.4	Locating module		A location module (also: locating module) is the combination of locating candidates with operation or operation sequences. All operations which are located in between a location module are supposed to be realised using the same locating candidate. In a locating oriented assembly systems, locating modules may also represent its assembly modules.	p.128

Preface

The research presented in this manuscript is not standing alone. On the scientific side, it is the result of three years of work at the LCFC laboratory at Arts et Métiers Metz. More specifically, in the research team on the design of robust product-process-production system. On the industrial side, it is the result of an applied research cooperation with our industrial partner, component and subsystem supplier in the automotive sector. In this high-competition sector, companies, especially suppliers, are under multiple pressures: customer requirements, product variety, competition and technological ruptures in sight. In consequence, classical dedicated production lines are failing to respond. A research cluster has been established between the LCFC, the partner company, and other industrial partners in order to seek answers responding to their industrial challenges. The research work presented in this document is part of a research project of the cluster and carried out as applied research in cooperation with industry.

This preface aims to give an overview of the research context of the research work which is presented in this manuscript. To illustrate the different challenges and the environment in which the research has been accomplished several points are introduced. First, the research laboratory is presented, putting the focus on its research experience and related research which has already been realised. Then, the industrial context is explained, emphasising the specific industrial challenges at the example of the industrial partner of this research. Finally, the applied research in the research cluster is explained and the research methodology is presented.

Research context

The research has been carried out at *Arts et Métiers Institute of Technology*, an academic institution offering engineering studies from Bachelor degrees to PhD titles. Spread over campuses in eight towns and having 14 research laboratories. In the following, the focus is put on the LCFC laboratory of the campus of Metz.

Presentation of the research carried out at LCFC

The LCFC, Laboratory for Design, Manufacturing and Control [LCFC 2020], is a scientific research laboratory located at the *Arts et Métiers Institute of Technology* and the *University of Lorraine*. It addresses research questions on identification, modelling and processing of scientific knowledge, phenomenological and technological, for the design, manufacturing and control of mechanic and mechatronic products and systems.

Its research activities seek to develop future production systems in the fields of services and manufacturing, which includes:

- developing tools to invent, design, organise, and control production systems;
- guaranteeing quality, safety and health at work;
- developing new manufacturing processes and their associated production systems, design features and assure their usability with high technological value.

In this context, the research comes within the scope of *Industry of the Future* issues. It considers the human as element of the system focusing on surveillance and anticipation, high-level steering, and system reconfiguration. Concerning production, flexibility and agility issues are addressed by robotics in manufacturing processes, innovative manufacturing and assembly technologies bringing high added value for product production. Reliable digital models with measurable performances and innovative methods of simulation and optimisation for products and processes come within the scope of virtual factories. All these topics are framed by three research axes which are “*Design*”, “*Manufacturing*” and “*Control*”. As the thesis research is integrated into the “*Design*” axis, its specific orientation is detailed in the following.

The aim is to develop specific and original methods, models and tools or adapt existing ones for the co-design of products, manufacturing process and production systems (PPS). The challenge is then to increase the performance of this triad, to control the causes that can disrupt them, and to improve performances. Taking into account the uncertainties that the PPS may encounter throughout its life cycle, robust solutions are developed as well as quantitative approaches (spreading constraints and uncertainties) and qualitative analysis (failure mode analysis).

Uncertainties can be of three types: random uncertainties, as epistemic uncertainties and variability of PPS during its life cycle. Consequently, the research on the “*Design*” axis is divided into three related topics: (i) mastering PPS variations, (ii) mastering PPS imprecisions and (iii) mastering variability and reconfigurability in regard of PPS. The last point presenting the **frame for the thesis research**, it is detailed below.

Mastering variability or reconfigurability includes the assessment of variability or reconfigurability degrees of a PPS based on requirements which can be: technological, life cycle, time, environmental, human, cost. This requires for a modular **product** design, to define a system of indicators characterizing module compatibility and the impact of this compatibility on product family performance. It requires for **process** design, to define a system of indicators characterizing the interoperability of sub-processes, the inaccuracies inherent in this interoperability and the impacts of these on the product performance. And, last, it requires for a reconfigurable **production system** (machines, equipment) to define its capabilities, module compatibility and controllability. It needs to be determined the feasible product families with their production performance.

Previous research work on PPS carried out at LCFC

In regard of the “*Design*” research axis on PPS facing uncertainty, two doctoral theses are to mention which have been realized in the context of the design and optimization of production processes and systems and which can be seen as forerunners and research work complementary to the one presented in this thesis manuscript.

In his PhD thesis, entitled “Co-design of milling processes and cinematic configurations of a reconfigurable production system”, Aamer Baqai proposes a new methodology for co-exploring the solution spaces of the machining processes and kinematic configurations of the production system [Baqai 2010]. It supports the integrated design of process and production system. To do this, a design framework based on the FBS approach (function-behaviour-structure) is formalised. It connects strategic and operational levels related to process determination and production. In order to explore all solutions at the operational level, an algorithmic approach is presented that generates machining ranges and kinematic configurations. For the selection of the solutions generated, performance indicators are defined, structured, and their evaluation methods identified. The adaptation of graphs and the use of simulation methods allow the validation of the generated machining ranges.

Qing Xia developed in his PhD thesis “Models and methods for the generation of reconfigurable manufacturing processes” a model, its use cases, and tools for the reconfigurable and automated generation of manufacturing processes on the level of both, part families and product families [Xia 2017]. It proposes an approach based on the function analysis of a product family by linking functional varieties to varieties of parts. The varieties of parts are represented by the variety of their characteristics. So, functional variety induces part variety induces characteristics variety. Using constraint satisfaction problem (CSP) approach and the expression of knowledge with the first order logic, processes are generated generically that contain all possible operation sequences.

Baqai's approach concerns the design of processes and the production system based on product knowledge. It takes into account parts families for the creation of reconfigurable production systems by examining machining processes. Xia's work focuses on parts families and manufacturing processes that do not take into account the limitations of an existing system.

Industrial context

The PhD thesis is carried out in cooperation with a component and subsystem supplier in the automotive sector. On several sites, the company designs and assembles component and subsystem needed by car manufacturers. In general, about one in seven cars worldwide is equipped with parts of the partner company. This means production with a high throughput and a product portfolio with various references.

The automotive sector is facing technological ruptures in this times: the decreasing importance of classical combustion drives in favour of an increasing electrification (with the fuel cell drive as potential alternative), the increasing connection (internet of things) and autonomous drives are the most common examples. Two examples for these new technology have been presented recently. One by Hyundai, a car manufacturer, integrating joysticks in the new concept of the full electric Hyundai Prophecy model [Demeule, Autoplus 2020]. And one by ZF Friedrichshafen, a supplier, presenting a new prototype for a car cockpit supposed to respond to the requirements for the cars of the future [Askari, Car&Driver 2020].

In addition to the product evolution mentioned above, the automotive sector, in which the partner company evolves, is marked by tough competition between the suppliers. It is characterised by strong concurrency and high dependencies between supplier and customer. The customers, i.e. the automotive groups as Volkswagen, Toyota, pass

through immediately harsh conditions on quality, delay, availability, and production volume which are a direct consequence of their own concurrency situation. In addition, to optimise their production, the customers give strict orders about the final design of the supplied product in order to integrate it with minimal efforts in their production. The market environment is marked by an increasing instability and more fluctuations which leads to an increasing number of product references and decreasing production volumes.

The **Figure 1** synthesises the challenging situation of suppliers in automotive industry. As mentioned, the supplier is under pressure from two sides: the customer side using its market power to impose his constraints in terms of price, delays and product design and the competitors side responding to the same request for proposals which means that it is necessary to be more reactive, faster and less expensive than him. In this environment, two objectives are of essential importance: First, to ensure the survival of the enterprise by winning offers and second to enlarge the room for manoeuvre as the environment is getting more difficult as the following examples illustrate.

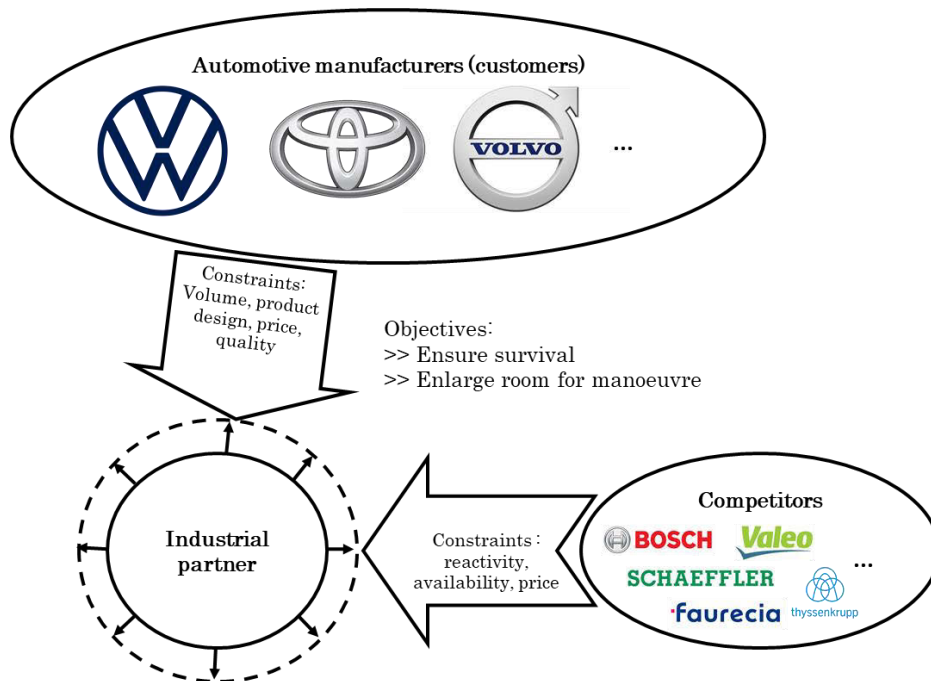


Figure 1. Industrial challenges

The production range of the partner company is distinguished by a wide variety of product families containing about 160 different references. The product range goes from simple components over standard subsystems to subsystems of high complexity. Although the functionality of each product and component family seems similar, they are designed according to specific customer requirements which leads to a great heterogeneity of physical realisation in particular concerning shapes and assembly technologies used. This heterogeneity does not represent any problem to the design of the production system as long as the demand is high enough to justify the investment costs for the installation and the change of dedicated production lines. In consequence, the common way of working is to get the bid for the production of a specific product and then to design its dedicated production line. A product family is therefore defined by the customer who gave the bid, as illustrated on the left hand side of Figure 2.

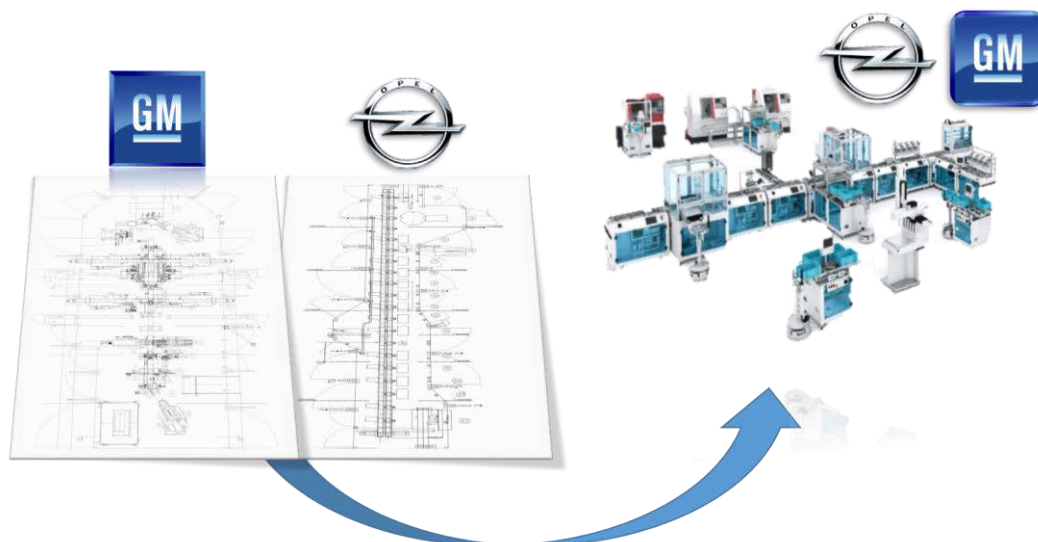


Figure 2. Dedicated production vs multi-products line

But this approach is considered not to be agile. Today, all companies are faced with a more increasing product variety, with unpredictable fluctuation in market demand and with technological ruptures in sight. The classical way of dedicated production is then not able to cope with these challenges. Possible industrial solutions to face challenges and enlarge the manoeuvre room are the following:

- Standardise and modularise product architecture to limit unneeded variety to mutualise production steps;
- Standardise technical solutions used in the product design to limit variety of production processes;
- Design production systems with reusable elements to increase the return of investment;
- Design production lines for multiple products;
- Increase the flexibility and reconfigurability of the production system;
- Adopt co-design approaches for PPS to increase reactivity.

From an industrial point of view, it is therefore necessary to develop methods that allow the analysis of products and processes. The aim is to derive out of these the requirements for the production system in order to achieve an agile and reconfigurable system which is adapted to various changes in the production range.

Applied research in a joint scientific-industrial research cluster

To answer to the industrial challenges described in the previous section, a joint research cluster has been established between the LCFC with its knowledge and skills on the design of robust PPS and industrial partners of whom the major part is represented by the UIMM Lorraine [UIMM 2020]. The research cluster set up at Arts et Métiers Institute of Technology Metz, is entitled “Chaire Arts et Métiers de Recherche Industrielle – Systèmes de Production Reconfigurables – Sûrs – Performants”. Financial support is provided by: F2i fund [Fonds-f2i 2020], industrial partners, Arts et Métiers Institute of Technology and the European Regional Development Fund under the grant name “Programme Opérationnel Lorraine-Massif des Vosges 2020”.

This research cluster, unifying high research experience with performant industrial partners, is dedicated to reconfigurable, safe and efficient production systems. It aims to answer the question "how to deploy the new technological bricks of the factory of the future to transform the production systems of small- and medium-sized enterprises (represented by UIMM) and industrial groups?" The research focuses on the design and optimization phases of production systems and acts on the following aspects:

- The adaptability and responsiveness of production systems to the variability of demands and products;
- Improving safety and health at work;
- Continuous improvement through a better understanding of the complexity of production systems.

To respond to these expectations, the research cluster has been divided into four challenges, each of them representing a distinct research project in the research cluster. These four challenges are the following:

- Challenge 1: Safe design of production systems - development and deployment of systems engineering;
- **Challenge 2: Design of modular and reconfigurable production systems for a product variety (context of this PhD research);**
- Challenge 3: Optimizing workers' manoeuvre margins in production systems for joint improvement of safety and health at work and industrial performance;
- Challenge 4: Continuous improvement of complex and modular production systems using data mining approaches.

The impacts of the research projects refer to different issues concerning the benefit of companies and also institutions focusing on humans at work. It raises awareness among companies about these issues and encourage the experimentation of new tools and approaches. The objective is to minimise change resistance by implementing operational actions and supporting the integration of the methods developed; adding additional value to companies which are supported in the search for innovation and improvement of their production system.

The research presented in this thesis report is located in challenge 2. It has been conducted in cooperation with the industrial partner, using their industrial experience and data for the development of new methods and tools. This industrial cooperation allowed the application of an iterative research method split into three phases: develop – experiment – analyse. The phase of developing includes state of the art definition and literature research to identify research gaps and the need for new methods and tools. The experimentation phase is used to apply already during early development stages the new concepts to real industrial use cases in order to test their maturity and efficiency and to verify their relevance. Finally, the analysis stage is used to identify change needs and optimisation potential of the new concepts. These stages are iterated as long as needed to obtain a satisfying result as illustrated in Figure 3.

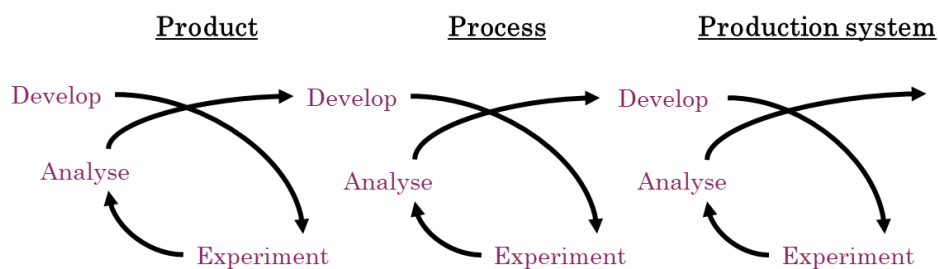


Figure 3. Iterative research method

In consequence, the industrial cooperation enables the immediate confrontation of the scientific concepts and newly developed tools to industrial reality. This way of working makes applied research more efficient in two ways: on one hand, it grants the usability of the concepts which have been developed in a laboratory environment and ensures that all industrial needs are answered. On the other hand, it allows to the industrial partner to have external input and to discover new ways of thinking which are not obvious from the pure application viewpoint. Finally, it helps to increase the acceptance of the new models, methods and tools, as they are presented early and their development has been illustrated with industrial use cases and has been accompanied by and optimised with industrial feedbacks.

Chapter I. Introduction

Since handcraft manufacturing, production paradigms have evolved a lot. During a certain timespan, mass production marked by low product variety has been the leading philosophy. Nowadays, industrial companies are faced with the challenge to combine the product variety of craft production with high developed industrial production systems, as the customer demands more and more personalised products. This evolution needs then adaptation. New paradigms as agility, flexibility, reconfigurability, etc., have emerged. In a first step, the different paradigms are compared and the vocabulary used in this research, i.e. agility, flexibility and reconfigurability, is defined. As reconfiguration is one of the main enablers for adaptable production, and as the presented research work is assembly oriented, it has been examined if literature on reconfigurable manufacturing can also be used for reconfigurable assembly; with positive outcome. Based on industrial challenges and current research streams the englobing research question has been defined as “how to design a reconfigurable production system considering product families and their assembly by addressing co-evolution aspects”. Based on this research question, three research aims are introduced. These structure the research work as well as this document.

In this chapter, through the development of market constraints, the evolution of production paradigms is traced. As the evolution of production systems needs adaptation, the general concepts of adaptable systems are summarised, the key words being agility, changeability, flexibility and reconfigurability. As the specific industrial challenges have been addressed in the preface, here the focus is put on the academic vision of them. Important vocabulary is defined in the text (grey boxes) which are also available in a definition glossary. A comparison between reconfiguration in manufacturing and assembly is done. Current research streams and questions are synthesised and the issue boundary of this research is defined. Based on the research gaps identified, the three research aims developed in this document are introduced and described. The structure of the present document is introduced using the three research aims and their decomposition as conducting element.

I.1. Evolution of production system paradigms

Since the first industrial revolution, production systems paradigms have been undergoing constant changes. A production system paradigm is to be understood as a strategy of how to organise the production. The evolution of these production system paradigms is strongly linked with the market environment. Whereas the mass production, introduced by Henry Ford, responded to a demand of cheap but

impersonalised products, the current customer is much more demanding. Steadily increasing demands on delivery time, product quality and variety lead to the continuous evolution of production. An illustrative overview of it is proposed by [Koren 2010].

The evolution from handcraft production over mass production to the diversification in the globalised world is traced. It can be seen that the current tendencies are higher product variety with constant or decreasing production volume. To cope with these challenging demands, concepts of co-evolution of products, production/assembly systems (and processes) have been introduced. So, [Bryan, Ko et al. 2007] propose a co-evolution methodology which is based on the joint design of a product family and its production system and on their later co-evolution. In addition, [Tolio, Ceglarek et al. 2010] add processes to the co-evolution perimeter. Thus, they consider the interactions, co-design and co-evolution of product, process and production system in their “SPECIES” approach.

Mentioning the need of evolution of production systems, it implies that the systems itself becomes adaptable. Analogous to Darwin’s survival of the fittest in biology, also for production systems the rule is “no evolution without adaptation”.

I.1.1. Evolution needs adaptation

In parallel to the evolution of production paradigms as illustrated in Figure I.1, the production strategies (towards adaptation of the production system) have evolved as well. It is well illustrated that a period already existed where product variety was very important: the period of artisanal craft production. Through industrial production, the product variety loosed influence. But today, customers gain influence by demanding customised products to distinguish themselves from the mass in a consumer society. The industrial companies are now faced to the challenge to adapt their (over)capacities to manufacture and assemble “craft” products on an industrial scale.

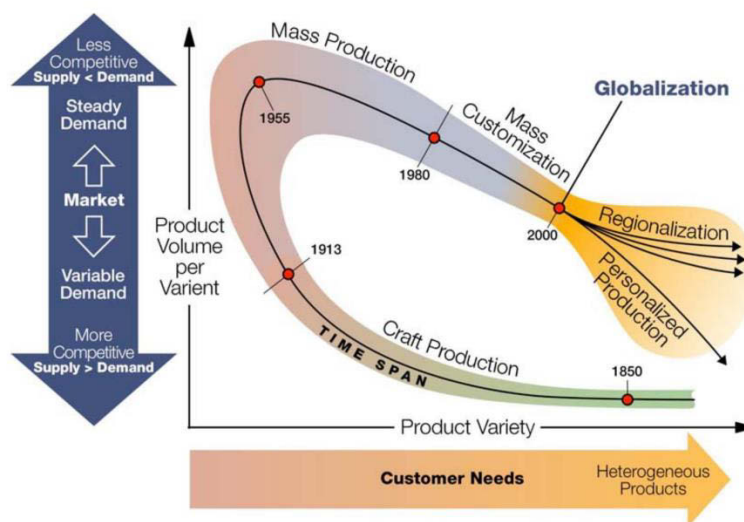


Figure I.1. Evolution of production paradigms [Koren 2010]

For this, the need of adaptable production systems is more and more increasing. Concerning adaptable production, different terms exist, describing different philosophies. The most common are: *agility*, *changeability*, *transformability*, *flexibility*,

and *change-over-ability*. As identical terms are used to describe different concepts, the wording in literature not being consistent and changing from author to author and by scientific community, we need in a first step to clarify the concepts and the vocabulary used.

The first distinction has to be made concerning the general focus which is technical and production system and design oriented. Often literature considers agility and flexibility as business concepts as described for example in literature reviews by [Sethi and Sethi 1990] on flexibility and [Gunasekaran 1998] and [Gunasekaran, Yusuf et al. 2019] on agility. This is not the point of view used in this research where both are seen as technical/technological concepts.

I.1.1.1. The concept of flexibility as part of agility

Throughout a literature review on what is *agility* and *flexibility*, [Abdelilah, ElKorchi et al. 2018] synthesise concepts and visions of both paradigms. They locate flexibility in the concept of agility. The former is seen as intrinsic capacity of a system to adjust in pre-defined settings. In this function it contributes to agility which is defined as strategic approach for rapid reconfiguration. It is stated that enterprises can shift from agility to flexibility.

In their statement of flexibility as intrinsic ability, the statement of [Abdelilah, ElKorchi et al. 2018] is similar to the concept of changeability versus flexibility developed by [Zäh, Möller and Vogel 2005] presented in the following section.

I.1.1.2. The concept of changeability versus flexibility

The definition of changeability is introduced by [Zäh, Möller and Vogel 2005] and [Nyhuis, Reinhart et al. 2008]. They limit *flexibility* as intrinsic capacity of the system to compensate fluctuations whereas *changeability* is needed to change the flexibility corridors and considers the whole production system including management, operation and information aspects.

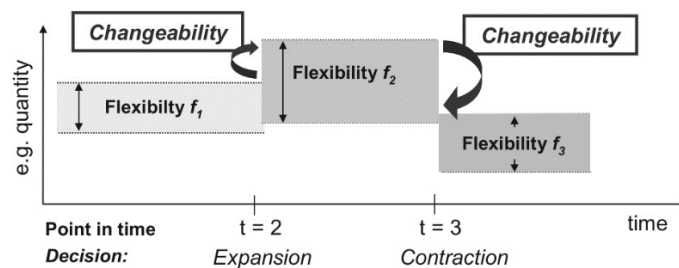


Figure I.2. Flexibility versus changeability according to [Nyhuis, Reinhart et al. 2008]

Reconfigurability concerns the level of workstations with the focus on technical aspects. Figure I.2 illustrates the difference between flexibility and changeability. The vertical axis may concern any relevant type or dimension of flexibility. An exhaustive overview of these can be found in [De Toni and Tonchia 1998] and [Yarain, Nadav et al. 2000].

This proposition is easily understandable and, furthermore, adaptable to different use cases and enterprises. It contrasts with the quite restrictive distinction presented in the following section.

I.1.1.3. The concept of changeability as umbrella term

One exhaustive definition has been proposed by [Wiendahl 2002], [Wiendahl, ElMaraghy et al. 2007] and [ElMaraghy and Wiendahl 2009] which defines the overall capacity of an enterprise to adapt as *changeability*. The overall changeability is declined into *changeability classes* on each level of product and production referring to a specific production paradigm. These classes are illustrated in Figure I.3.

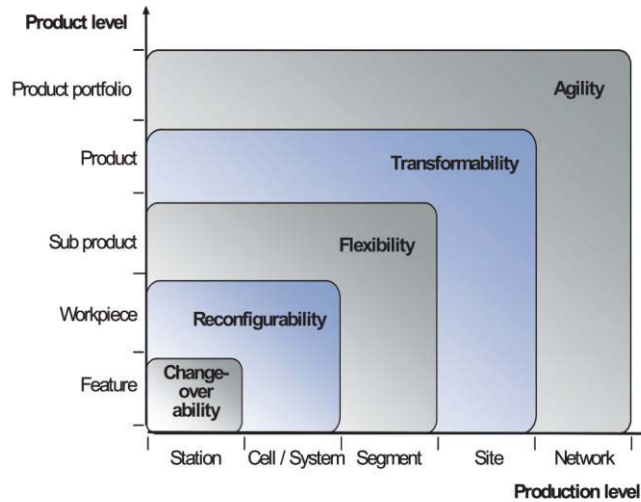


Figure I.3. Changeability classes according to [Wiendahl, ElMaraghy et al. 2007]

Thus, changeability is used as an umbrella term which regroups the other concepts. Particularly as the authors state that the distinction between flexibility and reconfigurability is not always clear.

However, despite the detailed definitions which are proposed, the article treats mainly flexibility. Furthermore, the distinct assignment of a production paradigm to a specific level of product-production limits voluntarily its application boundaries. This may not represent the whole applicability of the paradigms.

I.1.1.4. The concept of flexibility versus reconfigurability

Synthesising the results of a panel discussion during the 3rd Conference on Reconfigurable Manufacturing, [ElMaraghy 2006] dresses a comparison of *flexibility* versus *reconfigurability*. Stating that the main difference between the two paradigms is that the capacity and functionality of the latter is not fixed.

Despite this distinguishing characteristic, flexibility and reconfigurability are stated to not to be that distinct as stated for example in section I.1.1.2 or I.1.1.3. The frontiers between flexibility and reconfigurability are described as troubled and it is not clearly defined, finally, if reconfigurability and flexibility are distinct, if flexibility is a necessary aspect of reconfigurability or if reconfigurability is an improved flexibility.

So, if the source document is highly referenced in related literature, it furnishes no exploitable distinction of flexibility versus reconfigurability.

I.1.1.5. The concept of reconfigurability

In a comparison proposed by [Mehrabi, Ulsoy et al. 2000], adapted in Figure I.4, the latest big evolution step of production strategies has been the introduction of *reconfiguration*. A concept presented by [Koren, Heisel et al. 1999] and patented by [Koren and Ulsoy 2002].

Each production strategy responding to a particular aim in order to increase the competitiveness of the production in the changing market environments.

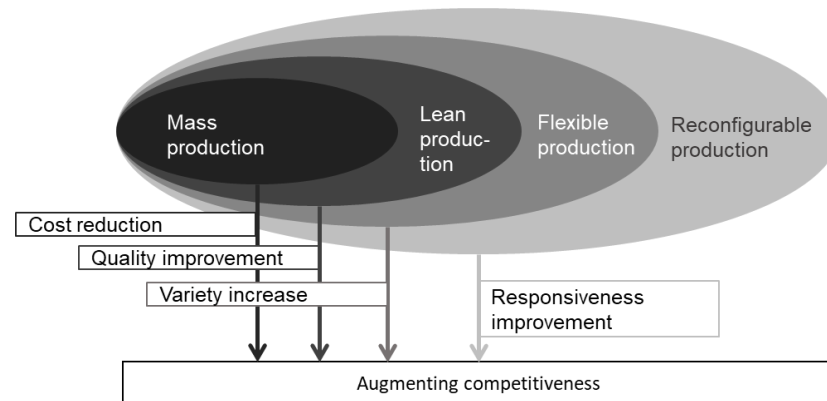


Figure I.4. Production strategies and their aims (adapted from [Mehrabi, Ulsoy et al. 2000])

The idea of reconfiguration is to design a production system which offers at any time the exact amount of flexibility needed to manufacture (reconfigurable manufacturing system – RMS) or assemble (reconfigurable assembly system – RAS) a given set of products. Reconfigurability is introduced to complete existing production strategies [Mehrabi, Ulsoy et al. 2002]. A reconfigurable manufacturing system is commonly defined as a system which “[...] is designed at the outset for 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 in response to sudden changes in market or in regulatory requirements [Koren, Heisel et al. 1999, p.529]”.

Issue of research for twenty years now, reconfiguration remains the latest development of production paradigms which seems to be the most promising approach for enterprises to face a difficult market environment. Even though literature on reconfiguration is plentiful, precise and successful applications on industrial scale are still rare, opening a wide field of applied research.

I.1.1.6. Definition of related vocabulary

As different notions have been introduced in the precedent paragraphs, it is needed to define in this place the important terms which are used in this thesis. In the following, only the notions of agility, flexibility and reconfigurability are used. These terms are used with the focus on technical aspects, whereas both, business and organisational aspects are not included. A summary of all definitions is added in the glossary.

Definition II.1: Flexibility

Flexibility is the intrinsic capacity of an element of the production system (e.g. workstation, module, cell, ...) to compensate external changes without modification.

Therefore, a distinct flexibility degree is fixed with the choice of a production facility. It is its operation range which is not changeable without modification. This leads to the notion of reconfigurability.

Definition II.2: Reconfigurability

Reconfigurability is the technical ability of an element of the production system (e.g. workstation, module, cell, ...) to be adaptable with modifications for external changes in production.

Thus, reconfigurability enables to change the flexibility characteristics of a production facility. In consequence, the overall agility of the production system can be described by the flexibility plus reconfigurability of its elements:

Definition II.3: Agility

Agility is the technical ability of a production system to adapt to external changes. These changes may be variations in demand or product mix. It represents the global potential of the production system including its reconfigurability and flexibility capacities.

The relations between agility, reconfigurability and flexibility are illustrated in Figure I.5. Agility can be described as the sum of the reconfiguration potential plus the flexibility potential of the production system.

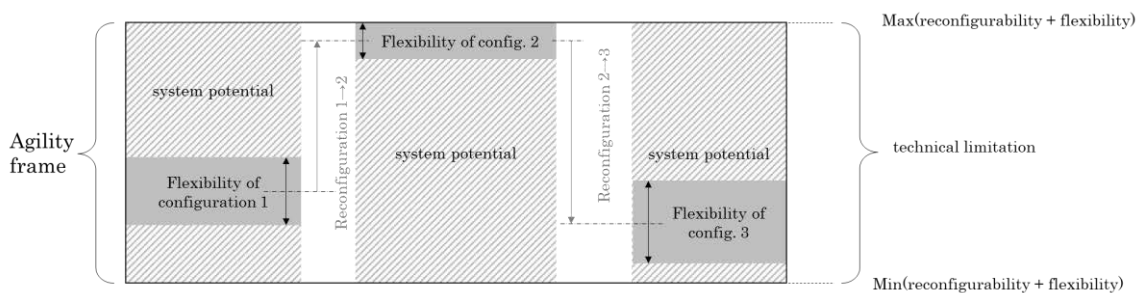


Figure I.5. Illustration of agility, flexibility and reconfigurability

The term of production systems is used frequently. As the research is focused on assembly, the term production system is synonym to assembly system. Manufacturing issues are not considered by the presented methodology.

I.1.1.7. Reconfigurable assembly versus reconfigurable manufacturing

In the precedent paragraph, reconfiguration of assembly systems and manufacturing systems is mentioned. However, existing literature is mostly manufacturing oriented. As the presented research is assembly oriented, it should be clarified what are the differences if they exist. First of all, it is to mention that the distinction between assembly and manufacturing systems is not always consistent in literature. On one hand, some articles consider RMS and RAS as equal, either implicitly or explicitly. On the other hand, there is a distinction of reconfigurability paradigms between assembly and manufacturing and a difference between their key characteristics. Table I.1 sums up the literature considering RAS and RMS equally at the left hand side and literature identifying differences at the right hand side.

Table I.1. Comparison of RAS and RMS in literature

RAS = RMS	RAS ≠ RMS
[Gyulai, Vén et al. 2012]	[Huettemann, Gaffry and Schmitt 2016]
[Weber, Stäbler et al. 2016]	[Koren and Shpitalni 2010]
[Bi, Wang and Lang 2007]	[ElMaraghy 2009]
[Andersen, Nielsen and Brunoe 2016]	[Wiendahl, ElMaraghy et al. 2007]
[Deif and ElMaraghy 2006]	

In general, it is found that if differences are identified between reconfiguration in manufacturing and assembly, they consist of adding supplementary key characteristics. A synthesised overview is furnished by [Rösiö 2012] who identifies eight key characteristics after a literature review.

To conclude it can be stated that the differences between RMS and RAS are not discriminant for the use of RMS literature on assembly issues as they have key characteristics in common.

Concerning research on reconfigurable assembly, [Gyulai, Vén et al. 2012], identify two principle fields of action: (i) the definition of an appropriate product mix and (ii) the detailed definition of the proposed production system. The former is in line with the idea that reconfigurable assembly is designed for a product family, the latter is vital for a good system design. Both issues are addressed by this research work.

I.1.2. Research directions concerning RMS and RAS

General research directions on reconfigurable assembly have been identified in a first literature review carried out by [Bi, Wang and Lang 2007]. They identify the following five research axes for research on reconfigurable assembly:

- Design for assembly as the product design heavily impacts and determines the design of the assembly system;
- New assembly processes and machines replacing the human work force which is often used in assembly systems;
- Modularisation and standardisation to increase the reusability of assembly system elements for different products;
- Automated robotic programming and intelligent control to achieve the software adaptation in reconfiguration;
- Integrated modelling and simulation give a decision making help as reconfiguration needs continuously decision to choose the best solution.

In addition to this assembly focused review, [Bi, Lang et al. 2008] identify research objectives on reconfigurable manufacturing. As stated in the precedent section, reconfiguration in manufacturing and assembly are addressed similarly. Thus, the four RMS research directions are presented in the following.

- Combination of RMS with other production paradigms as for example Lean Manufacturing to enrich the advantages of RMS with other characteristics;
- Development of a systematic design methodology for RMS addressing the need for new design methodologies, the need for system granularity determinations and the need of methods helping industrials to pass from non-configurable systems to reconfigurable systems;
- Configuration design when the number of reconfigurable variables (e.g. conveyors, fixtures, etc.) is important;
- Control design for real time adaptations and open architecture control design to enable modular infrastructure.

Finally, a recent literature review has been published by [Bortolini, Galizia and Mora 2018] on reconfigurable manufacturing. First, five research streams are identified.

- Stream 1: Reconfigurability level assessment;
- Stream 2: Analysis of RMS features, i.e. modularity, integrability, diagnosability, convertibility, scalability and customisation;
- Stream 3: Analysis of RMS performances;
- Stream 4: Applied research and field applications;
- Stream 5: Reconfigurability towards Industry 4.0 goals.

Beside these research streams, further research questions are identified as cited in the following table.

Table I.2. Research questions on RMS, synthesised from [Bortolini, Galizia and Mora 2018]

Research questions on reconfigurable manufacturing

1. Do industrial companies a clear view of the need of adopting the emerging production systems?
 2. Is it possible to make reconfigurable a production system not designed to be? Is it necessary to include reconfigurability principles just in the design phase of such systems?
 3. Is it possible to introduce reconfigurability principles in an existing production system without any substantial investment?
 4. What are the characteristics of an effective assessment method or indicator for RMS?
 5. How to evaluate a production system with existing reconfigurability indices? Do other reconfigurability indices need to be developed?
 6. Can current RMS measurements methods indicators and models be adapted to different processes and industries?
-

Using the research directions which have been identified by the cited authors, the hereafter presented research work is located in research stream 4 (applied research) and addresses the following topics:

- Design for assembly;
- Combination of RMS with other production paradigms;
- Development of a systematic design methodology for RMS.

In addition, it is located in the perimeter of the questions 2. and 4. presented in Table I.2. It proves that the research questions as introduced hereafter enter perfectly the current research streams and address issues which are of research interest.

I.2. Research questions

The concepts of agility, flexibility and reconfigurability are well-defined and analysed in research literature today. However, their implementation in industrial practise is not often realised, case studies are limited often to educative cases.

Addressing the lack of applied research, and in coherence with the statements of the previous section, the overall research perimeter is defined by the following research question:

How to analyse, measure and increase the agility of a production system?

In this perimeter, the focus is put on reconfigurability in the context of agility as defined before. A key question englobing the presented research is defined as follows:

How to design a reconfigurable production system considering product families and their assembly by addressing co-evolution aspects?

Out of this key questions, a set of objectives is derived. These objectives guide the research. They are gathered into in three aims, each addressing the three co-evolution aspects product, process and production system.

- **Aim 1:** Enable the analysis of products and product families characterised by product variety
 - Aim 1.1: Enable the analysis and structural comparison of products from product families
 - Aim 1.2: Enable the assembly analysis and comparison of product families

Aim 1 contains the product modelling. Generally known, a model is simplified representation of the reality, containing exactly the information needed for its use cases. Thus, it poses the basement for *Aim 2* and *Aim 3* which are use cases of the models developed in *Aim 1*.

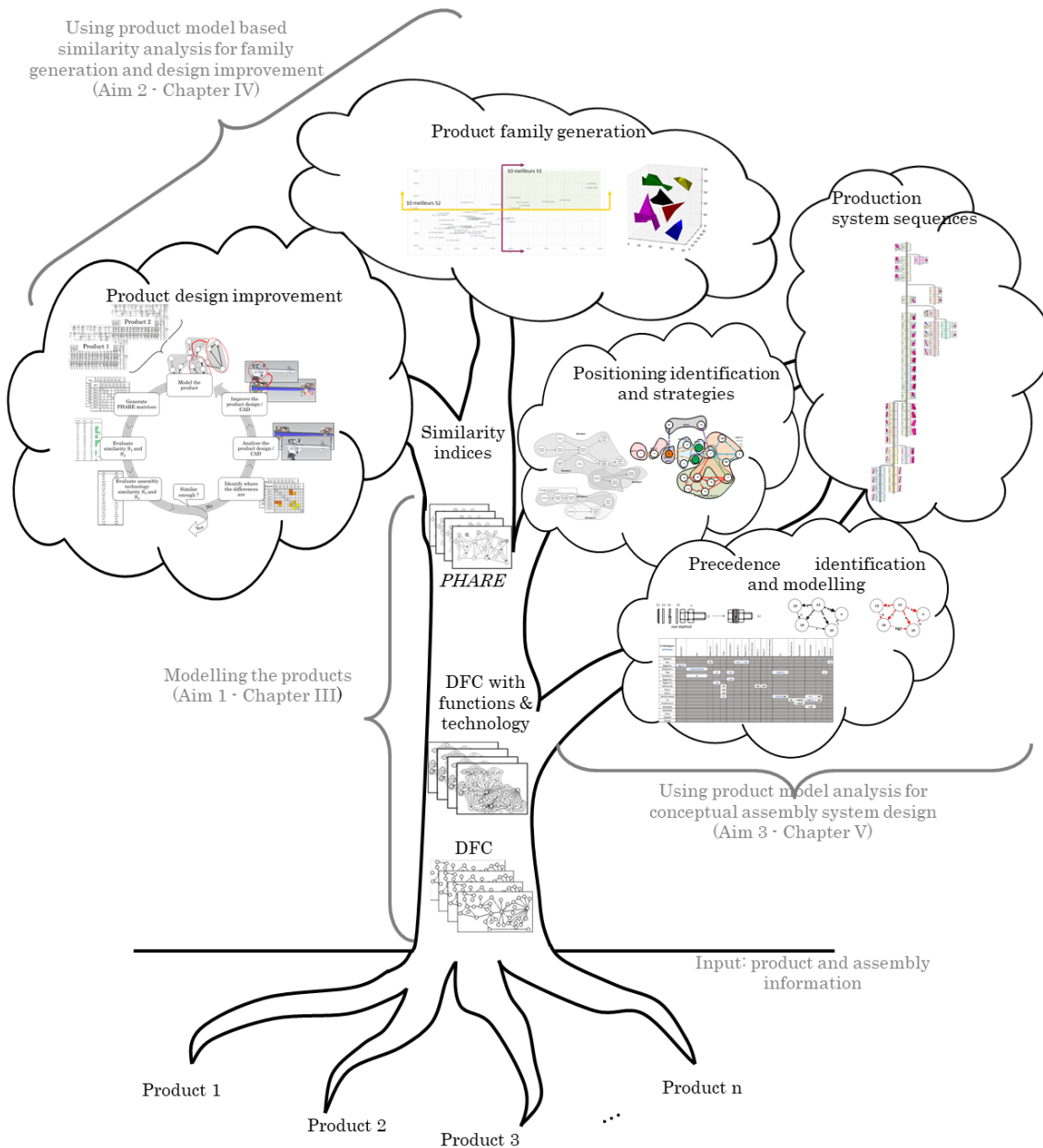
- **Aim 2:** Enable the identification or improvement of product families
 - Aim 2.1: Define indicators for product design similarity
 - Aim 2.2: Define indicators for assembly similarity

Aim 2 contains the generation of product families and their improvement. Improvement is meant in terms of structural and assembly similarity. It addresses the second part of the key question considering product families, their design and their assembly.

- **Aim 3:** Enable the preliminary generation of alternative assembly plans
 - Aim 3.1: Model and formalise assembly precedence constraints
 - Aim 3.2: Model and formalise assembly sequences based on locating strategy
 - Aim 3.3: Enable comparison of assembly sequences for product families

Aim 3 addresses the first part of the key question which is how to design a reconfigurable production system. It contains methods to generate a set of possible solutions for the production system, respecting a predefined set of constraints.

Figure I.6 gives an illustrative overview of the research aims. It emphasises their reasoning links, the models which have been developed and their use. The reading direction of the illustration is from the roots to the top. Given a set of products, the input is the product and assembly information (e.g. technical drawings, CAD files, part lists, ...). Out of these, the product models illustrated in the trunk are generated, beginning with the Datum Flow Chain (DFC) which is enriched with assembly information and information about technical functions, and out of which the physical and functional architecture is generated. These product models belong to *Aim 1* and are modelled with the methodology developed for this purpose. Based on these models, using combinations of them, the objectives defined in *Aim 2* and *Aim 3* can be reached, following the branches of the tree.



DFC = Datum Flow Chain, PHARE = Physical and Functional Architecture

Figure I.6. Synthesis of the research aims and their methods

Going to *Aim 2*, similarity analysis with four similarity indices based on the PHARE and DFC product models enables the structural and assembly comparison of product families affected by product and component variety. The similarity analysis can be used for two purposes: either for product design improvements (on the left hand side) by applying an iterative methodology to improve the similarity values modifying the product design and assembly technology choices. Or similarity can be used for product family identification (in the top of the tree), gathering products with high similarity values.

In regard of *Aim 3*, the two branches on the right hand side have to be followed. Precedence identification is based on the enriched DFC model. Locating strategies can be derived from locating identification based on a joint analysis of enriched DFC and PHARE model. Precedence and locating information leads finally to the generation of assembly sequence plans. For multi-product assembly lines, a comparison of these assembly sequence plans has to be done.

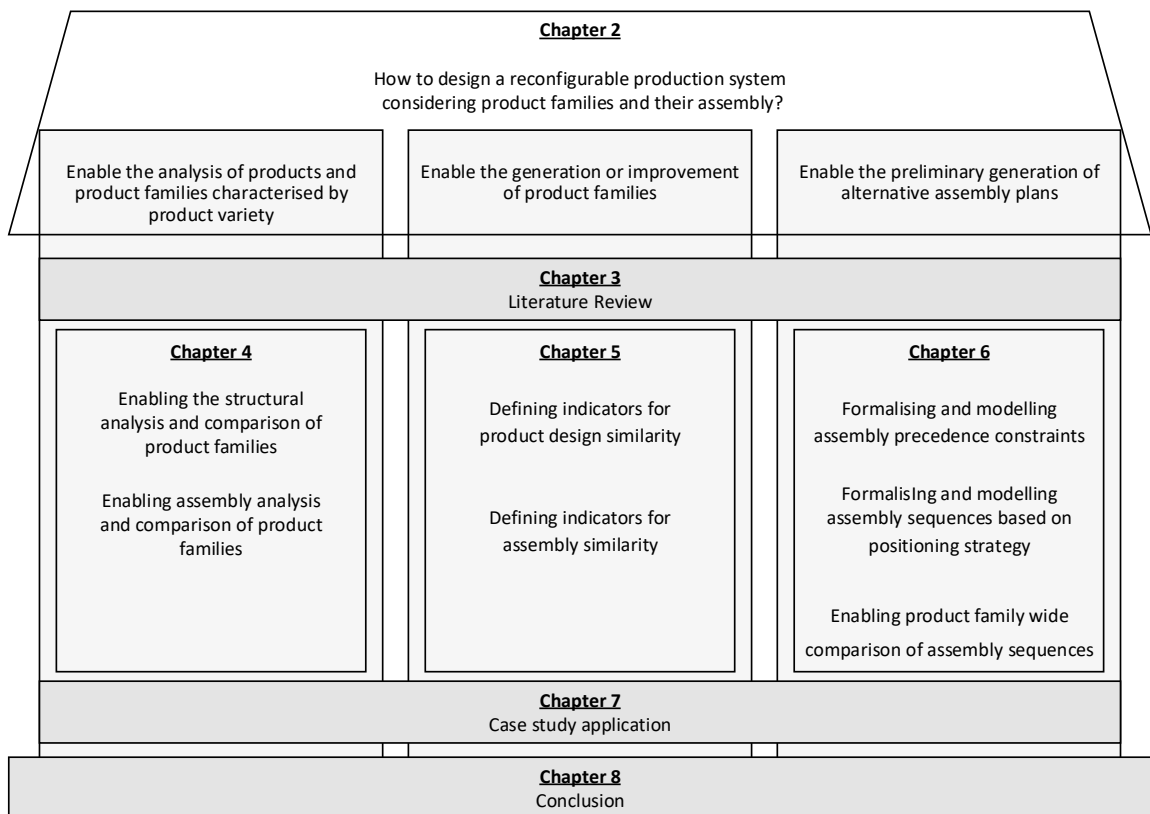


Figure I.7. Structure of the present document

It can be stated, that once the modelling part is finished, either *Aim 2* can be realised following the branches to the top, or *Aim 3* following the branches on the right hand side. Or both of them can be combined, the approach being adjustable for different use cases.

Not only the structure of the carried out research work but also the structure of this document follows the logic of the research aims. This structure is synthesised in Figure I.7. It is represented as a house with three pillars. In this chapter, the englobing research question is defined at first, then the three aims are derived, each representing one pillar.

The following chapter resumes the literature review carried out on each aspect which are addressed by the aims. The literature is discussed and their shortcomings are highlighted. The need for new models and methods is emphasised.

The third chapter addresses the elements of *Aim 1*. It details the models newly developed to enable the structural comparison of a product family (PF), addressed by *Aim 1.1*, and to enable the assembly comparison of a product family.

The fourth chapter is dedicated to *Aim 2*. It details the definition and calculation of indicators for product design similarity analysis (*Aim 2.1*) and indicators for assembly similarity analysis (*Aim 2.2*). In addition, their use for clustering and design improvement are presented.

In the fifth chapter, the elements of *Aim 3* are explained. At first, the method used to formalise assembly precedence constraints (*Aim 3.1*). Second, the formalisation of assembly sequences based on locating strategy, including the new method of identifying locating candidates (*Aim 3.2*). Finally, the use of precedence constraints and locating strategies to generate possible assembly sequences for the production system (*Aim 3.3*).

All methods and their usability are illustrated with help of educative use cases. A complete case study application is presented in the sixth chapter, detailing how the approach can be applied to a real industrial problem.

The seventh chapter concludes the proposition and gives further research perspectives.

Chapter II. Related Literature

Methods and tools on co-design of products and processes are now emerging to answer to today's challenging market conditions. However, approaches have been proposed earlier with upcoming robotics in flexible production. They are examined in the first part of the literature review. The approaches developed reach from conceptual design approaches, over design methods including specifically developed tools and analysis methods to the use of one specific tool based on biology analogy. However, they do either not address product variety or variety is considered with varying and unvarying components in products with same physical structure. This is not sufficient. A precise review on each research aim and sub-aim carried out what new developments are needed and which models can be used as starting point. It is stated that Datum Flow Chains are the best starting point for product modelling but lack information about assembly. In addition, a new physical and functional architecture view needs to be developed out of DFC to enable the comparison of product and component variety (aim 1.1). Concerning the assembly information, a new taxonomy and classification needs to be introduced in concordance with the product model as the existing ones are either not complete or not adapted (aim 1.2). Product and assembly similarity is thought to have a direct impact on production decisions (multi-product assembly system). For this new similarity indices based on the new models are needed because already existing similarity measures are not suited to answer to the research question (aim 2.1 and 2.2). Concerning the conceptual design, assembly plan generation is examined. The aspect of precedence constraint modelling is approached by identifying logical expressions as an adapted method (aim 3.1). Concerning the sequencing strategy, locating oriented strategies have been looked for, without a success. Thus, a new sequencing strategy based on component locating information needs to be developed (aim 3.2). Finally, the comparison of multiple product assembly sequences for a multi-product assembly line is examined and the adaptation of LCS/SCS methods identified as starting point.

This chapter is dedicated to a detailed literature review on concepts and methods which aim at the same direction as the research questions presented in the precedent chapter. Shortcomings and potentials of the approaches are highlighted and it is explained how the promising ones can be used later and where new developments are needed.

The structure is following the logic of the research key question and the research aims: At first, in a global review, entire design methodologies are presented and examined. The first part of the literature review is therefore dedicated to the englobing key question, how to design a reconfigurable production system considering product families and their assembly by addressing co-evolution aspects, and presents complete methods aiming at the design of adaptable assembly systems. The need for adaptation

has already been emphasised from an industrial viewpoint in the Preface and from an academic viewpoint in Chapter I.

Then, a detailed review on each research aim is presented, analysing literature on precise research problems. These research problems are the three research aims which have been presented. The review is conducted accordingly, the research aim being the structuring element. The structure is as follows: *Aim 1* (enable the analysis of products and product families characterised by product variety) is treated in section II.2.1. Literature on *Aim 2* (enable the identification or improvement of product families) is presented in section II.2.2. And a review on *Aim 3* (enable the preliminary generation of alternative assembly plans) is carried out in section II.2.3.

As before, definitions are introduced in the text – in grey boxes – where they are used for the first time. A complete overview of all definition is furnished in the glossary of definitions.

II.1. Methods and tools on co-design of product and process

Co-evolution aspects have been addressed in the beginning of the introduction. They have been emerging recently, advocating the idea of a simultaneous regard on product, process and production for the design of adaptable production systems. However, co-design methods have already been proposed with the emerging applications of robots and the issue of automated production (linked with early flexibility and agility reflexions). These are evaluated in this first section of the literature review, in regard to their capacity to respond to current industrial challenges and the englobing research question. The range of the literature reaches from conceptual design approaches (II.1.1 and II.1.2), over design methods including specifically developed tools and analysis methods (II.3 and II.4) to the use of one specific tool based on biology analogy (II.5).

II.1.1. Complete co-development method for automated assembly

In 1994, Rampersad developed a conceptual design method on a generic level. It is an integrated design method considering product, process and production system. Figure II.1 illustrates the interactions between these three aspects. Based on the circle of product, process and production system, a spiral design method is proposed passing from one aspect to another. Thus, the design consists of an iterative path passing repetitively by system, product and process, the cycle beginning with market research on the production system level.

The product design part includes three levels. The product assortment level, emphasising the need of component modularity and similarity. The product structure level, putting into advance assembly oriented product structures and Design for Assembly (DFA). Finally, the product component level focuses on modular design and part standardisation. The aim is to reduce variety of products, interfaces, modules and components. Analogous, the assembly processes are designed starting with the determination of an assembly strategy (including feeding, transportation and handling) which guides the system structure choice. At the end, assembly operations are chosen respecting constraints of cycle time. Integrate product and process improvement by redesign is achieved with the DFA house. At the end, system design is conducted with time studies, robustness considerations and cost and investment estimations.

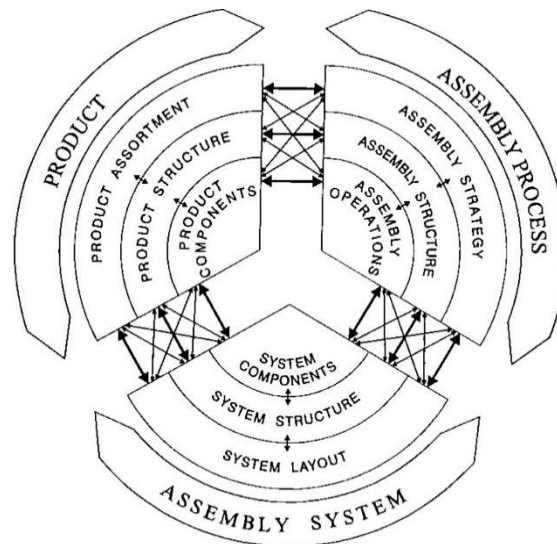


Figure II.1. Interaction between product, process and production system according to [Rampersad 1994]

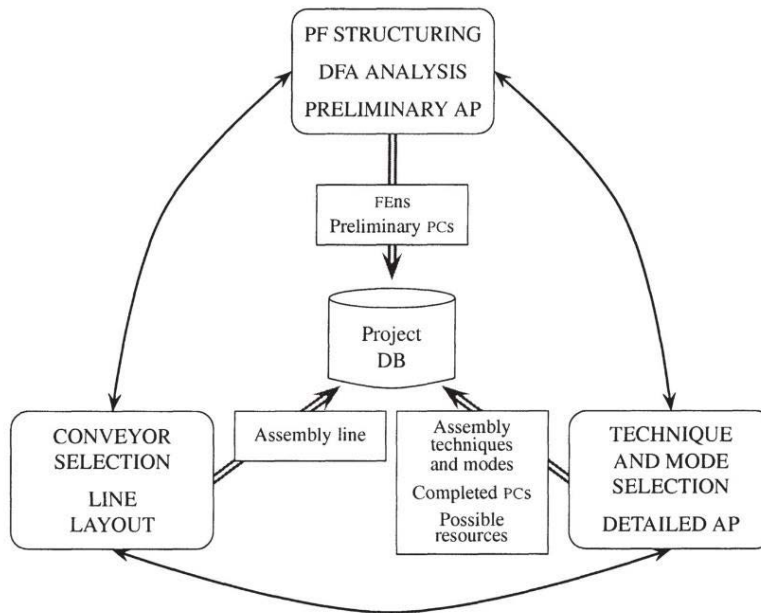
To conclude, the proposed integrated design process considers in a detailed manner the interactions between product, process and production system. For each design step, methods and criteria are detailed. However, the approach is carried out for one product which is to be assembled on one assembly system. Variety is only addressed as undesirable element which has to be reduced as much as possible. A strategy which does no longer correspond to a market environment demanding more variety. The successful application of the method presented by [Rampersad 1994] on product varieties or families has not been proved yet.

II.1.2. Integrated design of product family and assembly system

An assembly oriented method for the integrated design of product and production system has been presented by [De Lit and Delchambre 2003]. The overall approach is quite conceptual but mentioning nevertheless already existing tools and methods to support its application. An overview is presented in Figure II.2. The three aspects of product (on top), process (on the right side) and assembly system (on the left side) can be clearly distinguished. A short overview of the whole approach is provided in [Lit, Delchambre and Henrioud 2003]. Concerning the product part, the model relies mainly on product families, functional entities and generic components.

A product family is a set of product variants which are decomposed into two types of functional entities: common and specific. Each of them consists of functional entity variants. Therefore, combinations of functional entities define the product variety. The detailed description of the assembly oriented product family description is available in [De Lit, Danloy et al. 2003]. The functional entities themselves are composed of so called generic functional components and can include generic functional subassemblies and one dummy base part. The latter is a reference to a set of generic functional components. At last, it has to be noted that each generic functional component in the product family has at least one variant.

The product family is represented by an evolution of the liaison graph called generic liaison graph, containing the information about the cited main elements and their relations.



AP = assembly plan, DB = data base, FEn = functional entity, PC = precedence constraint, PF = product family

Figure II.2. Product family and assembly line design [De Lit and Delchambre 2003]

Concerning DFA, three main issues are addressed: complexity reduction, structuring which means the full exploitation of component variations to generate variations of functional entities and standardisation trying to design unvarying generic components if possible.

Preliminary assembly plans are generated using precedence graphs enriched with information about assembly directions in Cartesian coordinates, information about immediate and general precedencies and information out of the liaison graph by using the same node types for representation. The set of possible solutions is evaluated regarding the criteria of reorientations, parallelism, early/late generic components, stability and diversification (early/late).

Concerning the technique selection and detailed assembly planning (assembly process section), a taxonomy is proposed for assembly techniques. These are added on the precedence graph. After their selection, the product model is updated with chosen techniques and a detailed DFA is done on the product design for its optimisation in regard of the chosen technique. The assembly plans are updated consequently. Finally, the line layout treats the detailed planning of the assembly system, i.e. selection of conveying systems, workplaces and workplace organisation.

The proposition is exhaustive from product modelling to detailed assembly system planning, furnishing a lot of description and illustrative case study examples.

However, two shortcomings can be identified: The first one is the reiteration in the method when applying the technical solutions to the product model. According to the approach presented, the product model has to be updated because some technical solutions may alter the initial model. This can be very time consuming when the modelled assembly has numerous parts for which assembly techniques have to be detailed. The case study examples contain only around 20 components.

The second shortcoming is the quite restrictive definition of part families which are composed by component variants. However, no statement is done concerning different

components (which cannot be derived from the same generic component) having the same assembly technique. An assembly system could perfectly be able to treat them in the same way.

II.1.3. Liaison graphs and their use for assembly task and sequence planning

Product modelling by its functional link (“liaison fonctionnelle”) via liaison graphs emerged in the 80’s. Based on this product model, extended by several features, a co-design approach for product and production system has been developed. The new product representation has been introduced by [Bourjault 1984]: a functional link between two components exists if at least one mechanical link exists between them (functional link = sum of all mechanical links between two components). The representation of the whole product structure in a network allows the numerical exploitation of the models: assembly sequences can be generated following the paths in the network. The method is able to consider precedence constraints.

Based on the liaison graphs, [Bourjault and Lhote 1986] and [Bourjault 1988] developed an assembly process model. In this model, the state of the product being assembled is defined by realised liaisons.

In the following, [Bourjault and Henrioud 1987] extended the approach with the identification of subassemblies posterior to the definition of assembly sequences. The condition is that it must exist a sequence where realising the first links of the sequence correspond to the realisation of the links of a subassembly.

To do a next step in assembly sequence planning, [Bourjault, Chappe and Henrioud 1987] extended the liaison graph model to Petri networks. Each liaison corresponds to an action (to realise during assembly). An assembly sequence is thus defined by the sequence of actions. An elementary Petri network can be associated to any action. Thus an assembly sequence is modelled by combining Petri networks considering precedence constraints.

A method for computer aided assembly planning, transforming liaison graphs to assembly trees taking into account not only realisation of mechanical links but also complementary operations as quality control is introduced by [Henrioud, Bourjault and Chappe 1990]. The work leads to a computer aided generator which is called LEGA [Henrioud and Bourjault 1991]. It is extended by [Henrioud and Bourjault 1992] with precedence graphs and hypergraphs. An automatic method to generate precedence graphs out of assembly trees is introduced by [Chen and Henrioud 1994]. Finally, a detailed and updated method for their generation can be found in [Henrioud, Relange and Perrard 2002; 2003].

Concerning the assignment of assembly resources to the assembly plan, [Mînzcu and Henrioud 1993] introduce an algorithm to assign workstations to the precedence graph. For more flexibility in assembly planning, [Bonneville, Henrioud and Bourjault 1995] add the possibility of ternary operation (i.e. the realisation of three liaisons at the same time) to the assembly tree generation algorithm.

Using a product model based on the liaison graph model [Bourjault 1984], [Dufrène 1991] proposes a product structure for product families which has the focus on the sequence of assembly activities. Product families are decomposed into subfamilies according to one or more criteria.

The product family model being defined, [Stadzisz and Henrioud 1995] and [Stadzisz, Henrioud and Bourjault 1995] extend the LEGA software approach with the capability to deal with product families. Product families are defined with varying and unvarying components. Assembly trees are programmed with web-grammar which permits to define the component variations for each product in the common assembly tree. The product family model can be used for four different purposes: generation of assembly plans for a product family, discarding of non-promising assembly plans, generation of redesign advices and generation of constraints on product design [Stadzisz and Henrioud 1996].

At last, [Stadzisz and Henrioud 1998] couple the product family assembly tree with a predicate/event Petri net. Furthermore, they propose a whole integrated design methodology of multi-product assembly systems, using the previously mentioned models and work.

The design methodology consists of an iterative application of the following steps:

- Generation of feasible assembly plans;
- Discard of non-promising base components and non-promising assembly directions;
- Evaluation of the assembly difficulty and the required flexibility;
- Generation of design advices based on the assembly evaluation;
- Generation of design constraints based on the assembly process decisions.

Required flexibility of the system are workstations dealing with component variations of the product family. It has to be reduced when possible.

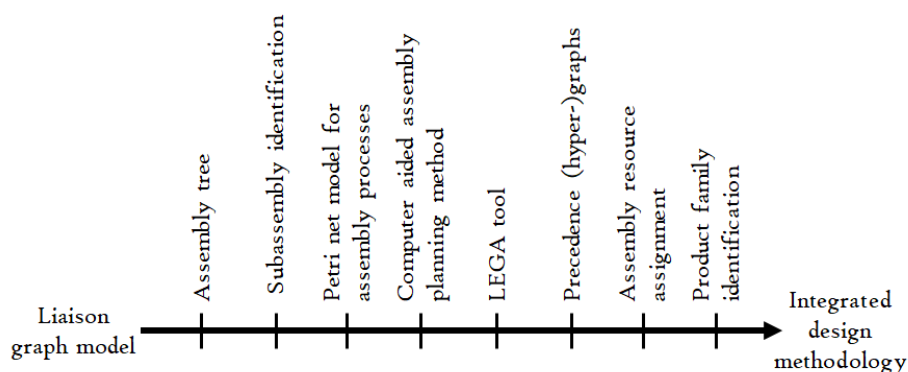


Figure II.3. Development of a multi-product assembly system design based on liaison graphs

The proposed modelling approach and integrated design method has been developed over two decades based on the initial proposition of modelling products with liaison graphs. Figure II.3 illustrates the development of the method with linked references.

The method is complete and has been tested and validated throughout many industrial case studies. However, two main shortcomings can be identified. First, the method has only been applied to small industrial case studies with a maximum of 40 components. The generation of all feasible assembly sequences leads to a combinatorial explosion of possibilities which have to be evaluated. Second, and more important, the product family is modelled with the same generic liaison graph and generic assembly tree. This means that all products of a family have always exactly the same number of components (varying or unvarying). This restriction limits the application of the methodology.

II.1.4. Assembly planning and system design with minimal assemblies

A specific method for assembly planning has been developed by [Maguet 1982] with the aim to contribute to the design of flexible assembly systems. It is a concept of assembly planning based on a decomposition approach and the identification of minimal subassemblies (stable component assemblies) and assembly boxes (assemblies realising a function and being already assembled; original French term: “boîtiers”). The subassemblies are identified by their assembly elements (“assembleurs”) which may be taken apart or not. Thus, a minimal assembly is composed of assembly elements and depending components or subassemblies. Assembly sequences are derived by decomposition sequences and precedencies are expressed in a decomposition graph.

Shortcomings of this method are that (i) no help is provided for the identification of minimal assemblies and the decomposition precedencies which are completely manual, and (ii) that the sequencing obtained concerns only the minimal subassemblies but not the components in the minimal subassembly.

The main elements and definitions of [Maguet 1982] have been overtaken by [Jeannes 1986] in a methodology to analyse and improve products for automated assembly. The method is divided into a macro-analysis to generate assembly processes and into a micro-analysis to detail production system design.

Focusing on the macro-analysis, an algorithm is proposed for the generation of precedence graphs (similar to decomposition graphs). Based on the precedence graphs which are a kind of hypergraph regrouping all feasible assembly sequences, assembly processes are deduced. An assembly process is seen as a specific sequence of assembly steps representing a branch of the precedence hypergraph. To reduce the number of possible solutions, more constraints can be added to the model via constraint matrices. At the end, the product redesign part aims to delete precedence constraints to generate independent sub-assemblies.

The main shortcoming of the approach is that process selection is done by a “*try-and-error*” approach [Jeannes 1986, p. 129]. In addition, no applications on part and product variety are proposed, the method focusing only on one particular product.

II.1.5. Cladistics for co-evolution of product and production system

The use of cladistics in engineering is a recent approach to model feature evolution of products. A recent specific application of this model which is commonly used in biology, in the context product and production system co-evolution, is the parallel use of cladistics on product and production system modelling. Co-evolution issues are addressed by projecting the product cladogram on the mirrored production system cladogram. Changes are induced to produce a perfect mirror image.

To forecast future changes in the production system, possible changes in the product cladogram are anticipated and the production system cladogram is updated accordingly. Vice versa, the same mechanism is used to adapt the product to predicted production system changes [AlGeddawy and ElMaraghy 2012]. A mathematical model and an algorithm for the application of the co-evolution approach are presented in [ElMaraghy and AlGeddawy 2012].

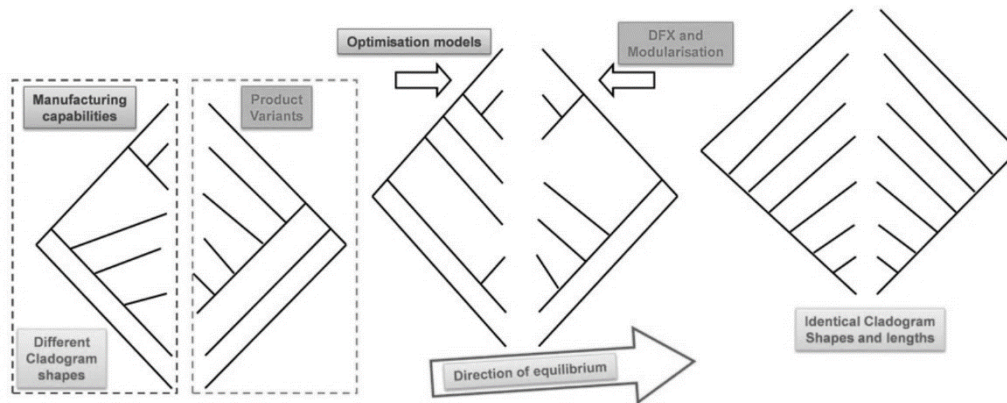


Figure II.4. Use of cladograms for co-evolution of product and production system according to [AlGeddawy and ElMaraghy 2011]

The cladistics based approach furnishes an illustrative model when applying to simple use cases. However, a detailed application to a product variety composed of an important feature and component variety has not been realised yet. Therefore, an efficient application of the proposed approaches to complex industrial problems is not proved.

II.1.6. Discussion

The analysis of the five presented approaches for integrated design of product, (process) and production system showed that the older approaches, initially dedicated to automated and flexible production system design, are not adapted to the new marked conditions with increasing product and component variety.

Some of the approaches do not at all consider the design of a product family including variety ([Rampersad 1994], [Maguet 1982], [Jeannes 1986]). Variety is not addressed and its integration in the approaches has not been anticipated. It is coinciding with the fact that at the time of their development standardisation was the leading paradigm and variety had to be minimised as much as possible.

Or, the approaches consider that a product family is composed of products having similar components, where similarity means that product variation is achieved by having some varying components which differ only in feature variation ([De Lit and Delchambre 2003], the liaison graph based method in section III.1.2). This variety definition is too restrictive today and implies at the same time that the products of a product family have always the same number of components. No statement is done about the design of production systems with similar products differing in component count or products having different components which could be assembled by the same facilities.

Finally, the most recent approach with cladistics (section III.1.5) remains too general and lacks detailed applications and explication how it could be applied to an important feature and component variety. The complete, integrated approaches having shortcomings which make them not applicable to answer the presented research questions, a more precise literature review is carried out in the following part which examines existing methods and models for each research aim.

II.2. Related literature by research aim

As mentioned, the structure of this section is following the structure of the three research aims introduced in the precedent chapter. To facilitate reading, the section titles are at the same time the titles of the research aims and the subsections represent the division of the research aims into sub-aims. For each element, the objectives of the literature review are detailed, related applications are summarised and the shortcomings of the existing approaches are emphasised.

II.2.1. Enable the analysis of products and product families characterised by product variety (Aim 1)

The literature review on *Aim 1* is divided into two parts. The first part is oriented on product structure modelling approaches as the analysis of different products needs to be done based on a common product model. The modelling approaches are evaluated regarding their ability to cope with variety, i.e. the question how variations in the product structure are represented by the models and what impact would the comparison of multiple products have on the representation, which means if one representation can be used for all products. The second part focuses on assembly technologies and processes. The aim is to enable a concurrent analysis of product and process. Therefore, for a complete product analysis, not only the structural product representation but also the representation of its assembly processes is necessary. Literature is identified with the aim to identify how to model assembly processes and to identify assembly technologies for classification.

II.2.1.1. Enable the analysis and structural comparison of product families (Aim 1.1)

In this section, literature proposing models and representations of mechanical assemblies is examined. [Whitney 2004] identifies the following approaches for assembly modelling which are used in industrial application: part lists, bill of materials (BOM), liaison graphs and Datum Flow Chains (DFC). In addition to these approaches, [ElMaraghy, AlGeddawy and Azab 2008] proposed a new method based on cladistics. Already presented in section II.1.5 in a co-evolution approach, they can also be applied on the analysis of product families. The part list is the simplest model which can be used as a starting point for the generation of the other representations (see Figure II.5).

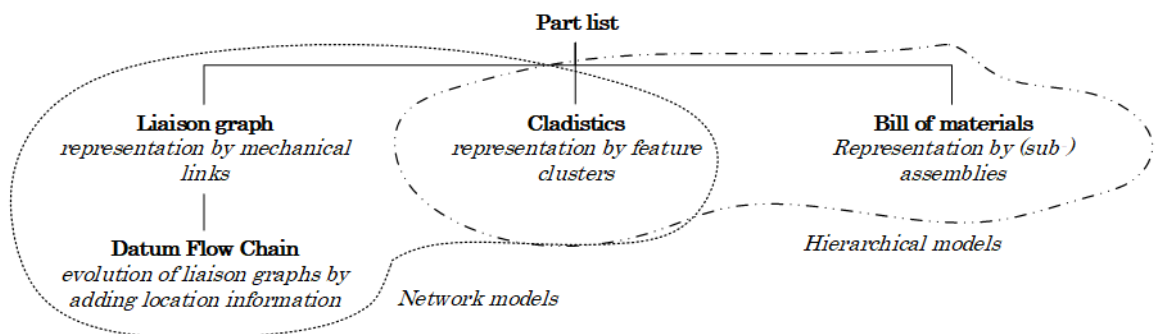


Figure II.5. Different assembly representations and their relation

As stated by [Söderberg, Lindkvist and Carlson 2006], hierarchical models are not suited to visualise all dependencies between the components making the use of network representations more recommendable for product analysis. Therefore, the following review focuses on the evaluation of network representations and the hierarchical network of cladistics, briefly defined below:

- *Cladistics* describe technical feature variation in one product family putting the emphasis not on its chronological but technical evolution. It is used to support the paradigm of delayed product differentiation [He, Kusiak and Tseng 1998].
- *Liaison graphs* visualise a product assembly in a network. Components are represented by nodes and their relations by links between the nodes. A link means that two components are in touch (mechanical assembly or simple contact).
- *Datum Flow Chains* represent an evolution of the liaison graphs by adding information about the relative positioning of a part regarding its surrounding parts and eliminated degrees of freedom on the arcs. An exhaustive description of the DFC generation with several examples and its applications in industry is presented by [Whitney 2004] and [Mantripragada and Whitney 1998].

The needed characteristics of the product model to correspond to the research aim are well known: The model has to be insensitive to product component variety, that means that variations in component number and type should not impact the product model in a way that product comparison is made difficult. Also, it should contain a maximum of information about the product assembly, e.g. locating information or assembly information, and if this is not the case their integration to the model should be possible. Finally, it should be easy applicable and ideally permit a software implementation, at least partially.

Liaison graphs have been used assembly sequence generation and identification of common components (Table II.1, top part). In regard of the criteria defined, liaison graphs and similar network models furnish only quantitative information about component connections and no data about the relation characteristics. Furthermore, all the mentioned methods are only applied either on one specific product or on one family of very similar products. These models contain too less information for further use.

Cladistics seems to be adapted for product family analysis on a general level, mainly focusing on components which are linked to product features. Several applications have been presented for this use case (Table II.1, middle part). However, the feature-oriented analysis does not deliver information about all connections between different components. The model itself gives no information about the product architecture. It seems adapted for very similar products which have a large common base. In consequence, modelling with cladistics seems less adapted to product families with a high variety of components which highly increase the number of nodes, branches and characters. It cannot be seen how the model enables the identification of improvement axes.

Table II.1. Product modelling approaches and their use

	Reference	Use
Liaison graphs and similar network	[Bourjault 1984] [De Fazio and Whitney 1987] [Demoly, Yan et al. 2011]	Generate assembly sequences with liaison graphs
	[Gupta and Krishnan 1998]	Identify common components in product families with liaison graphs
	[Homem de Mello and Sanderson 1990]	Generate assembly sequences with AND/OR hypergraphs
Cladistics	[AlGeddawy and ElMaraghy 2010a]	Algorithm for the automatic generation of cladograms applied on the analysis of a product family of electric kettles
	[AlGeddawy and ElMaraghy 2010b]	Generate cladograms applied on the analysis of a product family of belt tensioners for car engines
	[AlGeddawy and ElMaraghy 2013]	Generate cladograms applied for the representation of a car body in white
	[AlGeddawy and ElMaraghy 2015] [AlGeddawy, Samy and ElMaraghy. 2017]	Identify different granularity levels for product variety management
	[Moussa and ElMaraghy 2019]	Generate a master assembly network for changeable manufacturing
Datum Flow Chains	[Turner, Subramaniam and Gupta 1992] [Shukla and Whitney 2001] [Demoly, Yan et al. 2012]	Analyse constraints with DFC (of over-, under-, and properly constraint assemblies)
	[Marguet and Mathieu 1999; 2003] [Falgarone and Chevassus 2006] [Jun and Jun 2013] [Xu, Lin et al. 2019]	Analyse geometrical variation propagation with DFC
	[Mathieu and Marguet 2001] [Sellakh, Rivière et al. 2003] [Spensieri, Carlson et al. 2009] [Andolfatto, Thiébaud et al. 2014] [Hejazi, Biswas et al. 2016]	Analyse tolerances in mechanical design with DFC

DFC has been used mainly for tolerance analysis and propagation analysis of geometrical variations (Table II.1, bottom). It offers not only quantitative but also qualitative information about an assembly. This fact makes it interesting as product model, even if it does not satisfy all of the criteria. It is sensitive to changes of component number and type and has not often been used for the representation of part

and product families and a variation analysis within these families. Nevertheless, in between the models examined, it seems to be the most useful representation and a promising starting point for further development. One application of DFC on this aspect known to the authors is proposed by [Xia, Etienne et al. 2018]. It proves that the DFC has potential to represent product families being subject to product variety. This encourages the choice of this representation as starting point for the development of a new product representation insensitive to component variations.

II.2.1.2. Enable the assembly analysis and comparison of product families (Aim 1.2)

The literature review on product models has emphasised that no product model exists which already integrates assembly information. Thus, this information has to be added to fulfil the demand of research aim 1.2. To add assembly information and knowledge, a framework is necessary which defines those. This framework is furnished by a *taxonomy* which has to ensure the compatibility of knowledge and information with the product model (DFC has been identified as interesting) and a *classification* which defines the items (data) of knowledge and information. Two requirements have to be fulfilled: The classification has to be exhaustive enough to englobe all the assembly data needed for industrial application and taxonomy must be compatible with the product model. At the same time both should be flexible enough to be able to be adapted to changing use cases, technological evolution and product model evolutions.

In consequence, this part of the literature review resumes publications describing assembly technology, operations and taxonomies for technology description. In addition, assembly process selection procedures are listed if proposed. The summary of the scope of the references found is drawn up in Table II.3. In general, it can be stated that literature describing the two topics in an explicit way is hardly to find. Furthermore, literature is mostly manufacturing oriented. In this kind of literature, some assembly aspects are addressed in the category of *joining* but are not exhaustive.

For example, [Ashby 1999] proposes a taxonomy differentiating processes into kingdom, family, class and attribute. In parallel, the design of a system is decomposed into anatomy, unit part and attributes. Process selection according to [Ashby 1999] aims at matching both. A process is defined as “*a method of shaping, finishing or joining a material*” [ibid., p.246]. Joining includes the technologies of bolting, riveting, welding, brazing and adhesive bonding. Due to the manufacturing orientation of this reference, the description and taxonomy of assembly remains not exhaustive. Process selection is done with tables illustrating the process domains in regard of a specific criterion, analogous to the material selection tables.

In his general treaty on manufacturing technology, [Bolton 1985] divides assembly operations into applications on metal parts and on plastic parts. For metal parts he identifies four main assembly processes which are adhesive bonding, soldering and brazing, welding and fastening systems. For plastic parts, fastening systems are distinguished into thread systems and press and snap fits. Although a quite exhaustive overview of different operations is proposed, it lacks a general taxonomy regrouping the aspects of assembly.

[Leroy 1984] proposes an overview of assembly operations which are regrouped into permanent assemblies (welding, adhesive bonding, riveting, nailing, fitting clipping and moulding) and into non-permanent assemblies (fitting, clipping and screwing).

The enumeration already shows the ambiguity of this classification and, in addition, a taxonomy framework is missing.

[Rampersad 1994] proposes the following taxonomy and classification of assembly processes: assembly operations are classed into the categories feeding, handling, composing, checking, adjusting and special processes. The assembly operations in its pure sense is allocated to the composing category, including insertion and joining. Rampersad’s proposition is complete, however it remains general concerning the detailed operations.

Another exhaustive listing is proposed by [Marty and Linares 1999], using the three main characteristics “mechanical assemblies”, “welding and brazing” and “adhesive bonding”. But here as well, the proposition lacks a taxonomy framework.

For [Groover 2001], assembly operations are, beside processing operations, a part of manufacturing. He distinguishes permanent joining processes (welding, brazing, etc.) from mechanical assemblies with threaded fasteners and mechanical assemblies forming a permanent connection. The distinction is not very clear, the listing not exhaustive and no taxonomy is presented.

Based on a disassembly approach, [Parsa and Saadat 2019] define operation categories based on component handling and not on technology. In summary, the categories are the following: (i) push/pull operations, straight line motion; (ii) twisting and push/pull operations, straight line and twisting motion; (iii) inter-surface friction, straight line motion; (iv) inter-surface friction and wedging, straight line and twisting motion; (v) material stiffness, twisting motions. The approach being innovative compared with the classical technology oriented classifications, it lacks of exhaustiveness and a taxonomy permitting its adaptation is missing.

Table II.2. DIN 8593 series and its content

Standard Reference	Topic
[DIN 8593-0]	General
[DIN 8593-1]	Assembling
[DIN 8593-2]	Filling
[DIN 8593-3]	Joining by mechanical means
[DIN 8593-4]	Joining by processing amorphous materials
[DIN 8593-5]	Joining by forming processes
[DIN 8593-6]	Joining by welding
[DIN 8593-7]	Joining by soldering or brazing
[DIN 8593-8]	Joining by means of adhesives

A complete taxonomy with operation classification is proposed by Lotter and [Wiendahl 2012] based on German standards (DIN) and recommendations (VDI). It regroups operations of joining, part handling, control, adjustment and special operations. Especially the joining series standards (DIN 8593) are worth further examination. It should be noticed that the referenced VDI recommendation (VDI 2860) is no longer published and issue of actualisation works.

Concerning the DIN series, it is divided into nine parts, one addressing general issues and the others dedicated each to one type of joining as illustrated in Table II.2. The DIN series proposes both, taxonomy and classifications. The description in detail, however, is quite general and for all engineering purposes, including civil engineering. This fact makes it very general for a more specific application on mechanical assemblies in industrial engineering.

[Tompkins 2010] proposes a process selection method including six steps from the definition of elemental operations over the identification, analysis, standardisation and evaluation of alternative processes to the process selection. But no classification of process technologies nor a taxonomy is detailed.

As mentioned in the beginning of this section, both, taxonomy and classification, are needed to meet the requirements which make the realisation of aim 1.2 possible. In Table II.3 can be seen that only four of the examined references furnish both (in bold letters). As consequence, the focus is put on the analysis of these four.

Table II.3. References on assembly processes and their scope

Reference	Taxonomy	Classification	Selection
[Leroy 1984]		X	
[Bolton 1985]		X	
[Rampersad 1994]	X	X	
[Ashby 1999]	X	X	X
[Marty and Linares 1999]		X	
[Groover 2001]		X	
[Tompkins 2010]			X
[Lotter and Wiendahl 2012]	X	X	
[Parsa and Saadat 2019]		X	
DIN 8593 series	X	X	

[Rampersad 1994] proposes a taxonomy and classification which is too generic for the presented purpose as it is not only assembly oriented but includes also other domains as manufacturing. The largest scope is covered by [Ashby 1999], but the classification is not universal. An exhaustive view including taxonomy and classification has been proposed by Lotter and [Wiendahl 2012]. Unfortunately, a part of the references is no longer up to date. Finally, the DIN 8593 series offers a complete view of assembly operations but is too large in the scope of addressed engineering domains. To sum it up, several references on assembly processes and operations exist but none of them proposes an exhaustive view of operations and a taxonomy applicable to mechanical engineering. Nevertheless, the DIN 8593 series seems a good starting point for the generation of a taxonomy and classification usable for the research work and compatible to the product model.

II.2.2. Enable the identification or improvement of product families (Aim 2)

Aim 2 focuses on indicators and methods which should allow the comparison of products. Comparison means the evaluation of product similarities. Based on this evaluation, either it is possible to regroup products or not (clustering decisions) or improvement potentials, in terms of similarity and standardisation, can be identified by trying to increase the similarity indicator values. An early clustering approach is the Group Technology methodology.

II.2.2.1. Define indicators for product design similarity (Aim 2.1) and for assembly similarity (Aim 2.2)

Concerning the clustering aspect, there are three visions to describe clusters: sales or customer oriented, manufacturing oriented and assembly oriented. According to [De Lit and Delchambre 2003], the former two are well-described whereas the latter, assembly-oriented product clusters, are rarely mentioned.

Product clusters can also be described as product family. Recent definitions of product family characteristics can be found in [Xia 2017], [Baylis, Zhang and McAdams 2018] and [Zhang, Qin et al. 2019]. [Xia 2017] defines a product family as a technical domain with a range of variety components and a range of component attributes. [Baylis, Zhang and McAdams 2018] define a product family simply as product variants sharing components. For our use case, the definition proposed by [Zhang, Qin et al. 2019] is the fittest one.

Definition III.1: Product Family

A product family is “*a set of similar products [i.e. assemblies] that share common technology platforms but have specific functionality/features to address a set of market segmentations and meet particular customer requirements.*” [Zhang, Qin et al. 2019, p. 3].

An early approach for regrouping parts into clusters is the Group Technology (GT) method. The philosophy aims at grouping parts which require similar operations with machines performing these operations [Kusiak and Heragu 1987] and [Kusiak 1987]. The matrix defining this relation is called part operation incidence matrix (POIM). Group Technology approaches can be applied for the layout design of cellular manufacturing systems [Heragu 1994]. The cells are identified by clustering entries of the POIM, for example with the algorithm presented by [King 1981].

GT is manufacturing oriented and considers the ability of a machine to process a part. No variety is considered explicitly. It can only be integrated by assuming that machines have a certain flexibility. This means that a compatibility analysis has to be conducted before. Thus GT remains too general for product design and assembly similarity identification under variety.

More in detail, on the product family level, assemblies differ mainly in two main characteristics: the number of components and their types (i.e. mechanic, electric, electronic). Here, the similarity analysis comes in to, on one hand, identify families, and on the other hand improve the product design for a better similarity within a product family.

Table II.4. Similarity indices and their application

Name and abbreviation	Reference	Scope	Application
Degree of Commonality Index	[Collier 1981]	Product Family	Comparison on component level; average number of common component items per average distinct component part; improvement of system performance
Total Constant Commonality Index	[Wacker and Treleven, 1986]	Product Family	Comparison on component level; modification of DCI to be relative with an absolute boundary; objective part standardisation
Commonality Index	[Martin and Ishii 1996; 1997]	Product Family	Comparison on component level; extension to DCI considering the number of varieties offered; design for a minimum variety cost
Percent Commonality Index	[Siddique, Rosen and Wang 1998]	Product; Production line	Simple comparison (common divided by common and unique); analysis of product platforms
Product line Commonality Index	[Kota, Sethuraman and Miller 2000]	Product Family	Comparison on component level; benchmarking product families
Component Part Commonality	[Jiao and Tseng 2000]	Product Family	Comparison on component level; evolution of DCI considering component cost to favour sharing high price parts
Product Similarity Matrix	[McAdams and Wood 2002]	Product (binary)	Similarity analysis based on product functions weighted with customer needs
Similarity of product type i and j	[Abdi and Labib 2004; 2007]	Product (binary)	Simple comparison (common divided by common and unique); analysis of product platforms

Table III.4. Similarity indices and their application (continued)

Name and abbreviation	Reference	Scope	Application
Comprehensive Metric for Commonality	[Thevenot and Simpson 2007]	Product family	Comparison on the component level; trade-off between diversity and commonality and product redesign
Use of Jaccards similarity index	[Galan, Racero et al. 2007]	Product Family	Method based on matrix evaluations. Evaluation based on BOM and part-to-part comparisons. Criteria as reusability, compatibility and demand added doing one to one comparison.
Similarity Matrix	[Lai and Gershenson 2008]	Product Family (process-oriented)	Similarity is process based and evaluated using penalty scores regarding grasping tool, fixturing direction, insertion tool and fixturing
Commonality versus Diversity index	[Alizon, Shooter and Simpson 2007; 2009]	Product Family	Comparison on component level; determining ideal trade-off between diversity and commonality
Similarity (no particular name)	[Rakesh, Jain and Metha 2010]	Part Family; Operations	Simple comparison (common divided by common and unique); operations are represented in a product-operation incidence matrix (similarity is calculated by part operation sequences)
Procrustean Analysis	[Shih 2011]	Product Family	Calculation of bill of materials similarity with Procrustes method (distances between BOM)
Synergy (of interfaces)	[Lafou, Mathieu et al. 2016]	Product Family	Comparison on component level; analysis of interfaces synergy introducing a new variant

However, similarity measurement as presented in literature is marked by a wide range of definitions and methods. An exhaustive overview of literature concerning the use of commonality analysis in product family design is proposed by [Simpson, Jiao et al. 2014] (remark: it is a re-edition of [Simpson, Jiao and Siddique 2006] with significantly changed content, having by far more information on similarity evaluations and clustering than the first edition).

The following literature summary is focused on what is entitled as main studies including commonality indices and metrics [Pirmoradi, Wang and Simpson 2014]. In the literature presented hereafter, the term of commonality is used. It is defined as the number of components that are used by more than one product and is determined for a product family [Ashayeri and Selen 2005]. Table II.4, inspired by [Thevenot and Simpson 2006], gives an overview of these indices.

Beside the *Total Commonality Index*, all the indices proposed in Table II.4 have in common that they assess commonality on the component level (component-based indices). Thus, commonality exists if the same component appears in different products or if exactly the same operations are used for assembly. The *Total Commonality Index* considers part variety through the generic BOM. Variety is addressed by its occurrence probability, with the aim to increase the number of common parts. Compatibility analyses of the variety are not considered.

Assembly is only considered by the *Comprehensive Metric for Commonality*, the *Product Line Commonality Index* and the unnamed approaches developed by [Lai and Gershenson 2008] and [Rakesh, Jain and Metha 2010]. But commonality is also fixed on the criterion “exactly the same”.

There is a lack of research concerning the identification of similar components in product families which are characterised by part variety. These similar components might be assembled with the same production facility which means that a commonality of “exactly the same” is not necessary and might be a case of over-engineering. In addition, a component-to-component comparison becomes more complex with increasing component count.

Indeed, complex mechanical assemblies with different component numbers are complicated to compare with the above-mentioned component-based indices. Due to the heterogeneity, the effectiveness of a solely component based model is uncertain as it needs compatibility analysis (another one-to-one comparison). To illustrate: if a company has 10^3 component references, this would make 10^6 comparisons. And every new component must be compared to $\geq 10^3$ others which represents a huge work charge.

Similarity indices enabling the comparison of product variety, including component variety, should be detailed enough to give a precise evaluation of similarity and to point out improvement potentials. But, in the same time, they should be abstract enough to not be impacted by reasonable variety, the criterion exactly the same being too strict.

II.2.3. Enable the preliminary generation of alternative assembly plans (Aim 3)

Based on similarity analysis, the preliminary decision of product clusters for multiple-product assembly systems can be taken. The next step consists of the conceptual design of the assembly system via the generation of alternative assembly plans. Therefore, this section on *Aim 3*, begins with a focus on global methodologies for system design. Afterwards a detailed review focuses on the steps needed for assembly plan generation, starting with the question of how to model precedence constraints, over the definition of a sequencing strategy looking for approaches which put locating in the centre of interest and finishing with the question of how to compare assembly sequences of multiple products.

II.2.3.1. On the design of production systems

In literature, several methodologies to design a reconfigurable manufacturing (or production) system are presented. In general, a production system has to meet a requirements set of different nature which is sometimes contradictory. The design of a production system is in the very middle of this field of tension as shows Figure II.6.

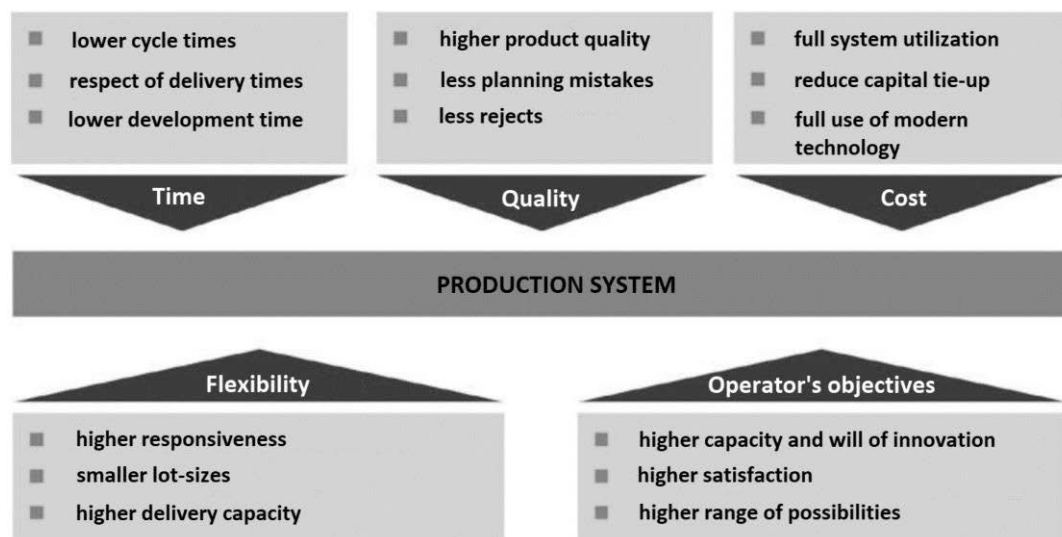


Figure II.6. Requirements on a production system, according to [Feldmann, Schöppner and Spur 2014], translated into English

In order to identify which work has been carried out on system design, the results of a literature review which aims to identify existing production system design methods are highlighted in the following.

Concerning a design method, already in 1998, Nam Suh and his co-authors asked the decisive questions: “What is an ideal manufacturing system?”, “How should we design a manufacturing system?” and “Can a manufacturing system be designed in a rational way based on scientific principles?” [Suh, Cochran and Lima 1998, p.627]. To answer these questions, they propose the application of axiomatic design principles. As three principle functional requirements, they identify increasing the sales revenue, minimising the manufacturing cost and minimising the manufacturing investment. Two possible design parameters are introduced depending if the manufacturing system is oriented on low-cost production or high-quality production. In conclusion, the article highlights

the necessity for a rational reasoning to achieve a set of functional requirements [Suh, Cochran and Lima 1998]. The axiomatic design approach has been evolved by [Arinez and Cochran 1999] who link product design parameters to production system design parameters creating a common process domain and in the manufacturing system design decomposition approach which is an iterative method to find the best design parameters for given functional requirements [Cochran and Arinez 2001].

Contrary to the axiomatic design approach, Deif and ElMaraghy propose a three-layer-structure for the design of a reconfigurable manufacturing system. The first layer consists in capturing the market demand and deducing design parameters concerning capacity and functionality. The second layer gathers the generation of different system configurations, the choice of one configuration and the reconfiguration planning for the chosen configuration. The third layer includes component level (re)configuration and implementation, taking into account time, throughput quality, cost, and customer satisfaction [Deif and ElMaraghy 2006]. Figure II.7 shows its IDEF0 representation. A use case, the adaptation of the three-layer-structure to the solar energy sector, has been proposed by [Alix, Benama and Perry 2014].

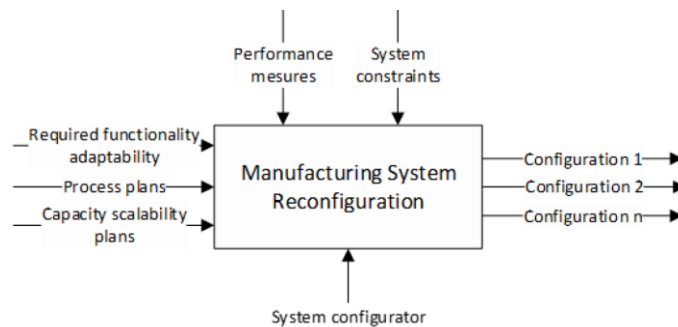


Figure II.7. IDEF0 for system level reconfiguration according to [Deif and ElMaraghy 2006]

[Vandaele and Decouttere 2014] propose a five-step framework for production system design which contains of

- stakeholder analysis and production system definition;
- definition of production system key performance indicators and requirements;
- scenarios generation and validation;
- ranking of production system scenarios;
- and production system scenario selection and implementation.

However, their framework remains on an abstract level and gives no precise information on application. [Rösiö and Bruch 2014] propose a framework focusing on the early design phases of initiation, project definition and conceptual design. For each phase, the purpose, activities and gate deliveries are defined. Unfortunately, the framework does not consider the concept of reconfiguration.

[Abdi and Labib 2003] propose an analytic hierarchy process (AHP) application for the comparison of an existing manufacturing system with an RMS and a hybrid (reconfigurable and existing) manufacturing system. The AHP categories (and their sub-categories) are evaluated under a short-term, mid-term and long-term point of view to identify an ideal alternative manufacturing system.

[Andersen et al. 2017] propose a generic design methodology for RMS by synthesising existing approaches into one framework. The overall structure reminds the traditional product design method proposed by [Pahl and Beitz 2001].

Another framework is presented by [Dolgui and Proth 2006] which base the production system design process on product design information in combination with commercial information (production volume, and so on.) as illustrated in Figure II.8.

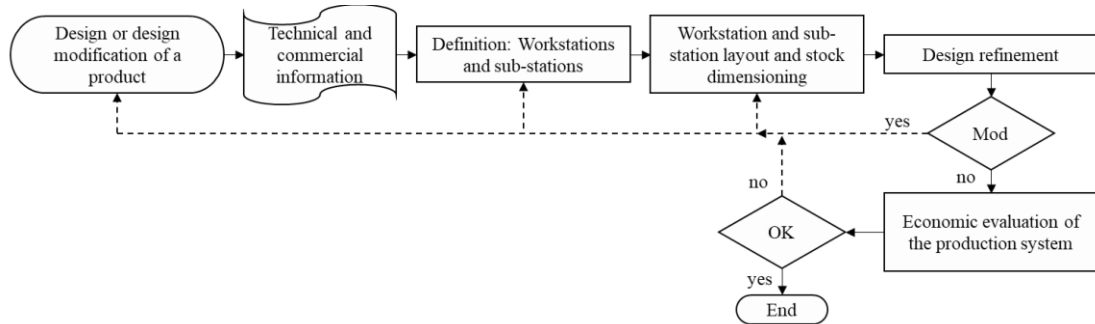


Figure II.8. Scheme of a production system design approach according to [Dolgui and Proth 2006], translated into English

[Arnauld and Renaud 2005] present a general framework for production system design which starts with the project definition and the choice of process types and models. The system design part itself is divided into the theoretical set up and the detailed set up considering project, functional, cellular and line aspects, as shown in Figure II.9.

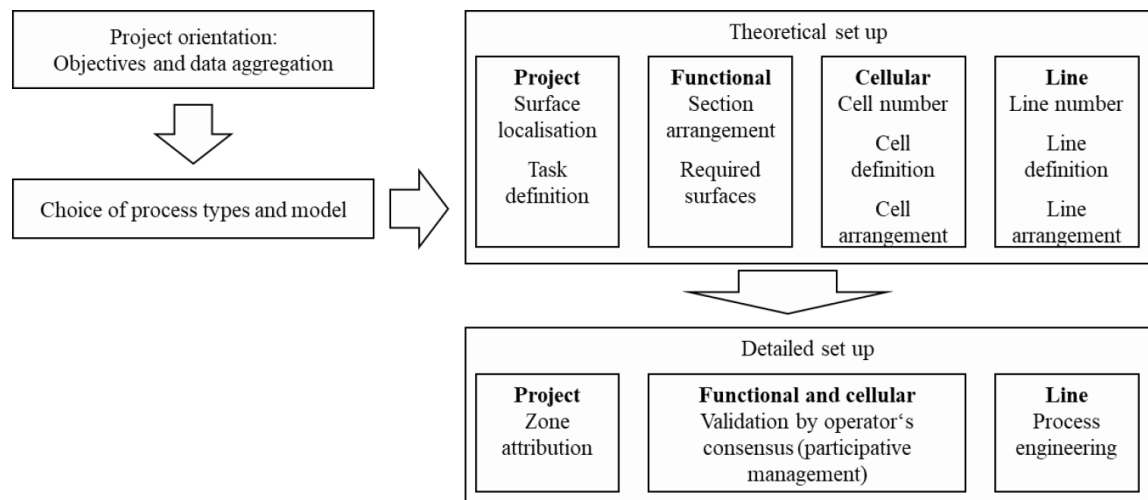


Figure II.9 Production system set up approach according to [Arnauld and Renaud 2005], translated into English

The need to use structured design methods is underlined by [Rösiö and Säfssten 2013] who highlight and emphasise at the same time that traditional approaches, like the approaches based on axiomatic design, do not support the concept of reconfigurability. At the same time, the traditional RMS literature describes methods and techniques to achieve reconfigurability but does not give much support to include ideas of reconfigurability in the production system design process.

A conclusion which is shared. The literature review on existing production system design methods emphasises a lack of design for reconfiguration. At the same time, the existing approaches remain on a conceptual and abstract level and provide very little support for choices concerning detailed problematics as for example the choice of optimum positioning solutions. A new product- and process-based approach is

therefore developed, aiming to cope with these shortcomings. The idea is that the key element to enable reconfiguration and multi-product assembly are the components which are located in the modules for assembly. Focusing on these for the conceptual design of the assembly system allows to identify compatibilities across the product portfolio and to organise assembly modules therefore in function of compatible locating elements and the belonging operations.

II.2.3.2. Model and formalise assembly precedence constraints (Aim 3.1)

Precedence constraints play an essential role in assembly planning as they limit the numerous possibilities of sequencing the realisation of mechanical links. For its definition one may refer to the following.

Definition III.2: Precedence Constraints

Precedence constraints “are the main links between the product domain and system domain [...]. [They] establish each product assembly sequence and determine the geometric and technological validity of a certain sequence of assembly processes.” [AlGeddawy and ElMaraghy 2010, p.5298]

On one hand, there are discriminant precedence constraints, i.e. precedence constraints which are necessary to assure the feasibility of an assembly. These are for example accessibility constraints or the interdiction of certain operation sequences. For example, [Waarts, Boneschanscher and Bronsvort 1992] distinguish two types precedence constraints: unstable assemblies and inaccessible assemblies.

[Henrioud, Bourjault and Chappe 1990] define operative constrains, i.e. whether an operation is feasible or not, and geometrical constraints which are accessibility related. On the other hand, supplementary precedence constraints which are not vital can be added, as for example constraints linked to weight or dimension variations. In this category, [Henrioud and Bourjault 1995] add material constrains (accessibility of the assembly tool) and strategic constraints of the company.

[Azab and ElMaraghy 2007] propose a set of six precedence constraints which can be distinguished in “hard” constraints (tool accessibility, dimensioning and tolerance constraints, non-destruction and fixture accessibility) and “soft” constraints which are logical operation sequences and good practises.

Both, essential and supplementary precedence constraints have to be represented. Thus, the following literature (Logical expressions are widely used for the representation of precedence constraints. According to [Marian, Luang and Abhary 2003], intrinsic precedence constraints can be directly derived from liaison graphs to logical expressions. Furthermore, modelling precedence constraints with logical expressions ensure a certain flexibility of the model allowing to add supplementary precedence constraints if necessary. At least, it can be at any time translated to a directed precedence graph.

Table II.5) focuses on how precedence constraints can be added. Assembly plan evaluation can be done using multiple criteria. For example, [Mascle 2002] proposes accessibility, stability, number of reorientations, parallel assembly and grouping operations.

Logical expressions are widely used for the representation of precedence constraints. According to [Marian, Luang and Abhary 2003], intrinsic precedence constraints can be directly derived from liaison graphs to logical expressions. Furthermore, modelling precedence constraints with logical expressions ensure a certain flexibility of the model allowing to add supplementary precedence constraints if necessary. At least, it can be at any time translated to a directed precedence graph.

Table II.5. Literature on precedence constraint representation and their scope

Reference	Model	Application
[Wolter 1991] [Wolter, Chakrabarty and Tsao 1992]	Logical expressions	Logical expressions ($<$, \leq , $=$, \neq) are used to represent all precedence constraints of an assembly in a data set.
[Gottipolu and Ghosh 1997]	Matrix with Boolean entries	Precedence and connectivity constraints are synthesised in a matrix concerning local and global feasibility. Assembly sequence graph is constructed out of the matrix.
[Lambert 2002]	Assembly graph	Use of assembly graphs derived from component oriented precedence relations.
[Niu, Ding et al. 2003]	Logical expressions	Set of logical expressions ($>$, and, or) which are translated to a precedence graph by an algorithm.
[Marian, Luong and Abhary 2003]	Liaison graph + logical expressions	Liaison graph for assembly representation. In its matrix, logical operators are used to express precedencies.
[Wang and Tian 2016]	Precedence graph with integrated constraint information	A precedence graph represents the geometrical constraints. Additional constraints are added on the arcs by expert evaluation.
[Kardos, Kovács and Váncza 2020]	Constraint model in linear programming for CAPP	Constraint expression conforming to linear integer programming. Connection of constraints with operators (and, or).

II.2.3.3. Model and formalise assembly sequences based on locating strategy (Aim 3.2)

In addition to precedence constraints, which are ideally limited to the vital minimum to not reduce unnecessarily the solution space, sequencing strategies may be applied. A promising approach is the identification of necessary locating elements for the assembly and their sequencing. Out of this, strategies minimising reorientation or repositioning can be applied.

Furthermore, in the context of multi-product assembly lines, locating plays an important role for the performance of the production system. Dedicated locating devices or product specific locating choices restrain the flexibility of the production system inducing supplementary, avoidable change needs.

Thus, the aim of this part of the literature review is to examine references on fixtures and fixturing in order to determine if approaches exist which use them to determine assembly sequences and which regard fixturing in the context of an agile assembly. This outcome guides the further research either to an adaptation of an existing approach or to a completely new development. So, the literature on locating and, more generally on fixturing (i.e. locating and clamping) is examined in regard of the question if locating strategies can be derived from the existing concepts. In addition, it is to examine what existing work has already been done on the classification and description of locating strategies. The question is therefore if a new concept of fixturing identification and application on assembly systems has to be developed.

Before evaluating the related literature, when talking about locating (or positioning), fixturing and clamping, at first, clear definitions of the terms linked to this topic are needed. For this reason, the definitions of [Gameros, Lowth et al. 2017], presented afterwards, are used in the following.

Definition III.3: Positioning/Locating

Positioning (synonym: locating) aims to remove degrees of freedom of a part in order to locate it in the three-dimensional space and in relation to other parts and to assure a needed orientation towards the assembly or manufacturing operation tool.

Clamping distinguishes from positioning/locating in the way that forces play an important role when clamping devices are needed.

Definition III.4: Clamping

Clamping has the aim to maintain a part at its location respective to any force applied by manufacturing or assembly processes.

This division into locating and clamping aspects matches with a literature review conducted by [Trappey and Liu 1990]. The parts which ensure the repeatable locating and orientation of the work piece are called fixtures and jigs. The difference between fixtures and jigs is, that jigs – in addition to the location and maintaining function – guide or interact with the machine tool. The following definition can be defined:

Definition III.5: Fixture

Fixture is called the technical element which realises locating and clamping, i.e. which ensures the location, orientation and stability of a work piece during manufacturing and assembly. It secures it against process forces.

In addition to fixtures, the term jig appears also in literature. To distinguish between them, a jig is a special case of fixtures who interact with the machine tool. Based on the common use of the term fixtures in literature, a new word, fixturing, is upcoming (even though it does not exist in the English language).

Definition III.6: Fixturing

Fixturing is an englobing term which describes the use of fixtures in order to achieve locating and clamping strategies. Thus it refers to the whole area from locating and clamping strategies to their technical realisation. Work holding can be used as synonym to fixturing.

The importance of fixturing during the production process is underlined by [Bakker, Papastathis et al. 2013] who state that fixtures have an important effect on the performance of a production line by the bias of its flexibility: Inflexible fixtures having

long change-over times can reduce the benefits of an automated and flexible production system.

However, even if fixturing is an aspect widely dealt with in literature and science, the applications and case studies are mostly focused on machining processes as cutting and milling. Assembly applications are not easy to find. So, [Boyes and Bakerjian 1989] state in their “Handbook of jig and fixture design”, reference work for fixture applications, that “*there never has been any standard or unique classification of these types of assembly fixtures*” [ibid. p.15-1].

Concerning the classification of fixtures, they propose the following ten categories in regard of the operation realised: riveting fixtures, drilling and pinning jigs, staking fixtures, crimping and swaging fixtures, pressing fixtures, tab-bending fixtures, wire-stitching fixtures, wire-stapling fixtures, special holding fixtures, masking fixtures.

[Arzanpour, Fung et al. 2006] propose the categories sensory-based fixturing techniques, modular and reconfigurable fixtures, programmable conformable clamps, phase change fixtures and adaptable fixtures. Another, similar, categorisation for fixturing is proposed by [Shirinzadeh 1995; 2002] and illustrated in Figure II.10.

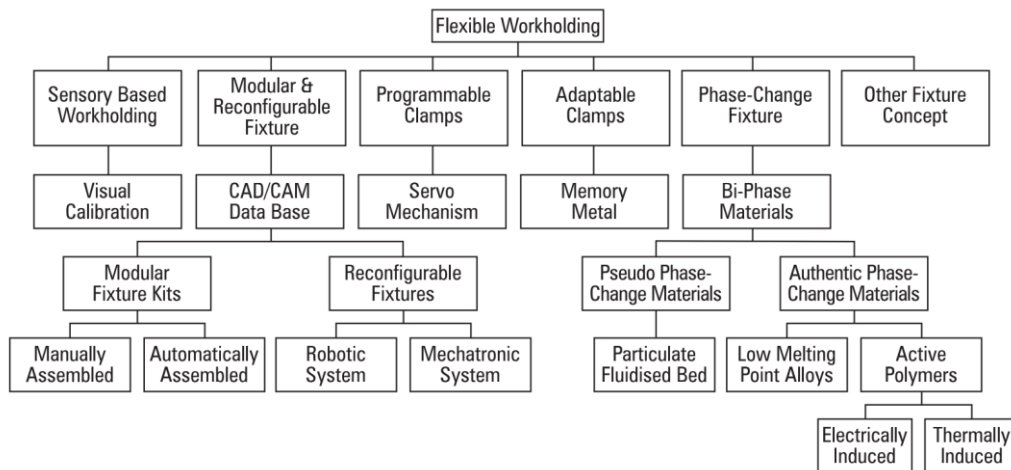


Figure II.10. Flexible fixturing categories [Shirinzadeh 2002]

Three further literature reviews have been identified synthesising the wide spread literature on fixtures and their applications: A comparison of computerised fixture design systems in respect to attributes as system method, design approach, part shape, part geometry, design consideration and CAD integration [Nee and Kumar 1991]. However, the examples focus on fixtures for manufacturing and the article is rather old and the comparison risks to be outdated.

The second review is presented by [Bi and Zhang 2001] who present a process for determining a fixture configuration and who propose a classification of flexible fixtures which is similar to Shirinzadeh’s classification presented in Figure II.10. At last, they give an overview of CAFD and set-up system application by naming the authors, applications and the used methodology. Its focus on computer-aided design approaches makes the review not persistent for the research.

Table II.6. Literature on fixturing applications

Reference	Scope	Application
[Wagner, Zhuang and Goldberg 1995]	M	Modular fixturing with seven supports for a manufacturing application, including automated verification of left degrees of freedom
[Park and Mills 2005]	A/M	Development of a smart gripping tool for thin sheet metals. Fixture compensates sheet metal deformations.
[Posselt and Wolke 2005]	M	Fixturing moving in a milling machine. Tools are fixed and the fixture is approaching them in a three-dimensional moving space.
[Kong and Ceglarek 2006]	A	Optimisation approach for entirely reconfigurable fixtures.
[Söderberg, Lindkvist and Carlson 2006]	A/M	Procedure for locating system selection for parts and subassemblies. Includes a location scheme library.
[Izquierdo, Hu et al. 2009]	A	Methodology to position fixtures in a robust manner for a product family of three different parts in a multi-stage production line. Focus on common fixture points on the parts.
[Yamaguchi, Furushiro and Higuchi 2010]	M	Application of a flexible fixture on a task which introduces a bolt in a hole.
[Papastathis, Ryll et al. 2010]	A	Aerospace application for a new fixturing design for the assembly and disassembly of high pressure rotors.
[Jonsson and Ossbahr 2010]	M	Overview of different ways to adapt reconfigurable fixtures (robot, manual, internal or external force). Focus on technical solutions for actuators.
[Martin, Muelaner et al. 2011]	M	Aerospace application for the control and validation of a real time adapting fixturing based on a hexapod system.
[Nelaturi, Rangarajan et al. 2014]	M	Automatic identification of non-fixture regions, fixture points and choice of adapted fixture in a supplier catalogue. In context of computer assisted fixture planning.
[Michalos, Sipsas et al. 2016]	A	Fixturing as part of a strategy of cooperating robots which share tasks and tools (and also fixtures).
[Erdem, Lewandowski et al. 2017]	A	Fixture design concept considering kinematics, actuation, position holding, control and software.
[Bejlegraad, ElMaraghy et al. 2018]	A	Design methodology for reconfigurable fixtures for a product family using a generic product representation.

A = assembly, M = manufacturing

Finally, [Boyle, Rong and Brown 2011] offer a review over computer aided fixture design approaches. They conclude that a greater focus is required on supporting unit design, and that there is a need to synthesise the diversified approaches within a framework furnishing an understanding of fixturing requirements for the fixture

design process. Only interesting part of their work are the requirements to meet for fixture design, they identify physical ability, tolerance respect, constrain respect, affordability, collision prevention and usability.

It can be stated that no literature review has identified the importance of fixturing and locating strategies for an adaptable production system. No application has been proposed which considers the locating as elementary part for the viability of multi-product production systems facing component and product variety. Beside the general literature reviews, some authors focus on specific problematics proposing more specified fixturing applications. This literature is quite diversified presenting different aspects, which are regrouped in Table II.6.

II.2.3.4. Enable comparison of assembly sequences for product families (Aim 3.3)

A quite instinctive way of comparing several assembly sequences is the search for common parts in the assembly sequence. The search for the longest common subsequence (LCS) or, related, the shortest common super-sequence (SCS) is a method which has been issue of research in mathematics and computer sciences for a while. Theoretical treatments on LCS concerning complexity boundaries of LCS and general LCS problems can be found in [Ullman, Aho and Hirschberg 1976] and [Maier 1978]. Some algorithmic solutions of LCS problems are reviewed in [Bergroth, Hakonen and Raita 2000].

However, their application to assembly sequence comparison is a recent field of research. Only few applications could be found in literature. They are summarised in Table II.7.

Table II.7. Assembly sequence comparison methods

Reference	Model	Application
[Gupta, Jain and Kumar 2012]	POIM	Similarity is calculated out of the Part Operation Incidence Matrix. A PCA analysis is used for classification and k-means algorithm for clustering.
[Goyal, Jain and Jain 2013]	BMIM	Similarity coefficient evaluating by-pass moves, idle machines and handling moves with LCS
[Wang, Huang et al. 2016]	LCS/SCS	Similarity coefficient and clustering based on LCS/SCS, idle machines and by-pass moves.
[Jiang, Wang et al. 2019]	SJMF / LCMF	Similarity model to estimate reconfiguration efforts
[Huang and Yan 2019a]	LCS/SCS	Similarity with LCS, weighted with process time and demand considering the impact of process time and capacity demand. Clustering is done by setting a similarity value as threshold.
[Huang and Yan 2019b]	LPCS	Combining Jaccard's similarity with LCS analysis for the design of delayed RMS (searching optimum place for reconfigurable stations).

Effectively, the use of the LCS/SCS principle on sequence comparison problems seems an efficient way to identify common and distinct sequence parts. This is an important issue in the design of multi-product assembly lines.

One shortcomings of the evaluated approaches are their orientation towards manufacturing and not assembly. Another is that component variety is not taken into account because the comparison criteria proposed are one-to-one comparisons of parts or stations. Concerning the one-to-one comparison of stations, it is not detailed, how the ability of stations can be included.

To conclude, the application of LCS/SCS methods to a whole multi-product assembly system has not been proved yet. It should be studied which aspects of these models could be applied on the presented research question.

II.3. Conclusions of the chapter

Related literature is divided into two types: methodologies describing the entire design process of product, process and production system as presented in paragraph II.1 and literature on a precise aspect which occurs during the design process, as presented in paragraph II.2.

The entire design methodologies offer a complete description of the design process detailing all the steps. However, even though some of them consider product variety and multi-product assembly lines, the concept of product variety is addressed by the comparison of components (varying and unvarying). This understanding of variety is too restrained in the todays market environment where variety is essential to the survival of a manufacturing firm. Thus, a more modern understanding of variety is introduced in the following, which is not solely component oriented but uses a hybrid view on physical architecture and technical function structure.

It enables the analysis and comparison of differing products and product families by similarity comparison. Similarity in product design and in the assembly technologies used are indicators for the similarity of the production system needed for each product. The hypothesis is that the similarity is reached through from the product level to the production system level. It means that products having high similarity are very likely to be assembled on a same multi-product assembly facility. The second part of the literature, addressed aim by aim the issues which needed to be clarified to enable the conceptual production system development via product similarity analysis. Its conclusion is presented by research aim:

- Aim 1.1 – Structural comparison: Out of the examined models and applications, the Datum Flow Chain is the one having the most potential. For this reason, it has been identified as starting point for a new product model. Less, some adaptations are needed to provide a DFC oriented representation enabling the hybrid view mentioned above. A new hybrid representation is derived out of the DFC (Chapter III) which enables the structural comparison of product families with product and component variety.
- Aim 1.2 – Assembly taxonomy and classification: As no product model includes assembly information, literature has been evaluated in regard of their capacity to fit with the product model and to be complete. It offers a wide spread set of taxonomies and classifications. DIN classifications are the most detailed and can be used as starting point. However, a new taxonomy is presented (Chapter

III) which is adapted to the models which are developed to answer to the research questions. This taxonomy answers at the same time to the concrete industrial needs and to the demand to be adaptable enough for other use cases.

- Aim 2.1/2.2 – Similarity analysis: Similarity analysis methods have similar shortcomings as the design methodologies. They are lacking a way to consider product variety due to their orientation on components. Furthermore, assembly operations or technologies are very rarely considered. Therefore, completely new assembly indices need to be developed, dealing with product variety and its assembly (Chapter IV).
- Aim 3.1 – Model precedence constraints: There are many different methods to model precedence constraints. The most common is the use of logical expressions. The approach based on liaison graphs seems to be adapted to the present problem. Logical operators are adaptable to any cases and can be translated later to precedence graphs for further exploitation (Chapter V).
- Aim 3.2 – Locating strategies and assembly sequences: The focus was put on locating strategies. Literature is very heterogenic addressing very specific issues. No method having a real potential for locating strategy definition could be identified. Thus, in the following work, a completely new way to identify and use locating in assembly is developed (Chapter V).
- Aim 3.3 – Assembly sequence comparison: Beside the SCS/LCS approaches, no other concept has been identified for the comparison of assembly sequences. Even if the entire application of these approaches is doubtful, their criteria can be adapted for a use on the newly developed models (Chapter V).

To conclude, a detailed literature review on existing methods and approaches has been presented. All the literature has been examined for their suitability in regard of the presented research questions. Research lacks are emphasised as well as concepts having potential being, even partially, integrated in the newly developed methodology. The further part of the document details now, as indicated in the conclusion of the research aims and following their structure, the concepts newly developed and their applications.

Chapter III. Enabling the Analysis of Products and their Families

This chapter focuses on research Aim 1, enabling the analysis of products and their families. Concerning the analysis of product structures, classical methods have been identified to fail to enable comparison of product variety. A new product representation is developed, the hybrid physical and functional architecture representation (PHARE). It is generated out of a Datum Flow Chain which is modified with the addition of functional subassemblies. These represent the realisation of technical functions in a product. The definition of technical functions for a product range furnishes an invariable framework enabling the comparison of products differing by variety and overcoming the shortcomings of classical approaches. The PHARE, therefore, enables the comparison of products and their families and the identification of their functional design. In addition, as beside the structural comparison also the comparison of used assembly technologies is an objective, a new taxonomy and classification of assembly related information is developed. It ensures two essential functionalities: The compatibility of assembly information with the product model and the consistency of assembly vocabulary and information over a time span and for a multitude of products. To gather assembly information out of industrial practise, a tool is introduced. Finally, assembly technology is added to the product model. Thus, two new models are introduced and their generation is described which enable analysis of products and their families.

The key question of the research work is how to design a reconfigurable production system considering product families and their assembly by addressing co-evolution aspects in the context of product variety. This question becomes more important as industrial companies have to produce nowadays a multitude of different product references to stay competitive. However, the classical way of production with product dedicated assembly lines reaches its limits. To enable and support the introduction of new multi-product assembly facilities, both, products and assembly technologies needs to be modelled and analysed. It should be considered that a product variety on the component level does not always imply a variety on the assembly system level. Thus, the models need to fulfil several requirements linked to challenges of product variety analysis:

- The models should provide a view of the product structures and their architecture;
- They should be able to reflect product variety being at the same time consistent for a set of products having similar functions;
- They should integrate assembly technology information in a consistent way.

These problems are addressed by research aim 1: enable the analysis of products and product families characterised by product variety. Based on the literature review on this research problem, the following conclusions could be taken:

- Several different product modelling approaches exist which represent the product structures and architectures;
- However, the granularity level of all of these models is situated on the component level. This means that product variety has an important impact on the product models and consistency of the models is not assured for a set of products having similar functions but differing components;
- Finally, assembly technology information is rarely integrated to the product models, and, in general, classifications of assembly technologies differ widely.

Out of these statements, the roadmap for the further development is defined. As a plenty of product models do already exist, the development has not to start from zero. However, the existing model has to be enriched about an additional dimension to cope with product variety. This dimension has to be linked with the product functions as products may have a set of varying components which differ heavily in component count and type but realise similar functions. In addition, assembly technologies need to be defined, in terms of a taxonomy as well as classifications, and added to the product model.

All these issues are addressed in the following sections. The first part of this chapter describes the new product models developed for analysing products under variety. The second part describes assembly technology knowledge and their integration to the product models. The chapter focuses on the models and tools which are developed and describes the way how they are generated. Their use and applications are described in the following chapters, in compliance with the structure presented in Figure I.6 and Figure I.7 in Chapter I. A summary of the modelling approach has been presented in [Stief et al. 2018].

III.1. Enabling the structural comparison

This paragraph addresses the question of the new product model coping with variety. It is situated in research aim 1.1. The literature review has carried out that no product representation is capable to enable the comparison of products having not only a set of varying components but which differ heavily in component count and type but realise similar functions. Nevertheless, Datum Flow Chain has been identified as starting point for the new product model development as it contains the most information of the examined product models and as it has been used for modelling in a related topic, the generation of reconfigurable process plans. Therefore, at first the construction of DFC is reminded. Then, the necessary modifications of the model are described. The modification is done with two adaptations. Finally, the transformation of the modified DFC to the physical and functional architecture is detailed. The data structure of the product models is available in Appendix A.

III.1.1. The Datum Flow Chain

In the literature review section on product models, DFC has been identified as the most useful product model, despite its shortcoming which is the component based modelling making product variety comparison difficult. Compared with the other models, it contains the most information and has been used for product modelling in the context

of product variety analysis. This makes it an ideal starting point for a new model development.

Detailed description of DFC and its applications can be found in [Mantripragada and Whitney 1998] and [Whitney 2004]. For better understanding of the here presented approach and because DFC is one of the fundamental bricks of the research work, it is described thoroughly in the following.

DFC is a graphical representation of a product assembly. Each product component is represented by a node. The mechanical links between the components are indicated by arcs. The direction of the arc defines a positioning relation. An arc from node a to node b means that component a positions component b . It should be noted, that there is at maximum one arc between two components which means that an arc represents a complete mechanical link between two components. If there is no mechanical link but only a contact between two components which does not fulfil any function, this relation is indicated by a dotted line in the DFC.

The number of degrees of freedom (DOF) between two components, which are eliminated by the mechanical link, are indicated by numbers on the arcs. In the hereafter used DFC representation, the thickness of the arcs is adapted in function of the degrees of freedom eliminated (the more DOF eliminated, the thicker is the arc). The standard notion of degrees of freedom is used which considers three translational and three rotational degrees of freedom in the Cartesian coordinate system ($T_x, T_y, T_z; R_x, R_y, R_z$).

Example III.1: Basic DFC

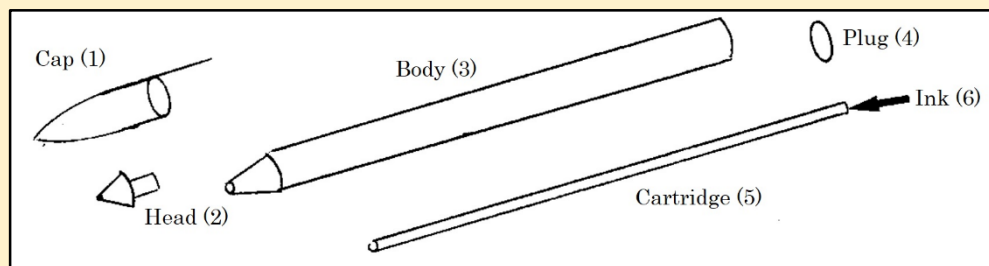


Figure III.1. Ball pen components

Figure III.1 shows the product components used for the basic DFC illustrated in Figure III.2. The illustration is taken from [Bourjault 1984, p.37].

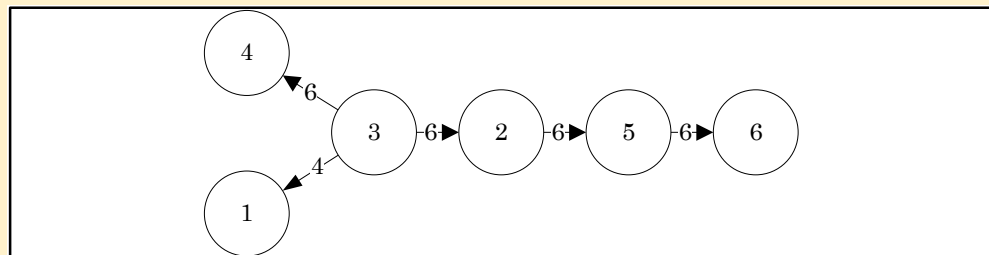


Figure III.2. Ball pen DFC

It can be considered that all components are assembled eliminating six degrees of freedom, beside the cap which can be turned and put off the pen. Furthermore, it is considered that all the positioning relations start from the body as central part.

As explained, the arc directions contain positioning information. For complex assemblies, when the positioning relation can be ambiguous, a convention has to be defined to assure that the DFC model for any product is constructed in the same way. That means the propagation of positioning information has to be consistent for all products examined by using the same base part which is the starting point for the DFC construction.

It should also be noted that fixture elements (i.e. screws, nuts, rivets, etc.) are considered as components. There is no distinction between components and fixture elements. At last, the DFC representation is a picture of the final assembly of a product. Temporary assemblies or mechanical links which are realised in more than one step are not represented. The DOF indicated on the arcs are the DOF eliminated once the mechanical link is completely established.

The following section details now, how the DFC model is translated to no longer be dependent on components, their number and type and which enables in this way the analysis of products and their families.

III.1.2. Technical function framework

As stated, component-based comparisons are not suited for product variety evaluation. Therefore, the component based DFC model has to be moved to a more abstract dimension. The aim is to generate a representation which is not impacted by product variety, i.e. which is generic enough to remain stable for products changing in component type and number. This is achieved with the **addition of technical functions** to DFC. Technical functions must not be mixed up with elementary functions of the product or customer needs defined during functional analysis. They are defined in the following.

Definition III.1: Technical Function

A technical function is a mechanism of the product that must satisfy its technical requirements. It is the translation of customer needs to design parameters. If a technical function is realised it contains at least one component. The components realising the same technical function do not need to have mechanical links between them.

To support variety comparison, a set of technical functions has to be defined which is common to all products to compare. It is a referential out of which the technical functions of the examined products are extracted. Depending on them, the number of realised technical functions may vary, however the number of available technical functions is the same for all products that are to be examined. **Product variety is then expressed by the use of technical functions and the relations between those.**

The definition of technical functions restrains voluntarily the application of the product models to products of the same domain which can refer to a common definition. To give an example, the method enables the comparison of a biro, a pencil and a feather pen but is not adapted to compare a feather pen with a water kettle. Though it is restrained by its assembly orientation, the approach remains generic and flexible.

The essential modification of the classical DFC consists now of the addition of technical functions to the basic model by allocating components to technical functions. The information content of the product model is therefore enlarged. It is assigned to the vertices of the graph (components). The allocation concerns exclusively the

elementary technical functions and is represented in the graph by coloured zones. The technical function containing components is called a functional subassembly. Analogous to the generation of different DFC, it should be noted that it is absolutely necessary that a consensus exists about the question which components belong to which functional subassembly. To enable a reliable comparison, the same allocation philosophy has to be employed.

Example III.2: Technical Function Framework

Referring to the previous example, the ball pen, one may imagine to compare a product family consisting of several pen types, including the ball pen, as illustrated in Figure III.3.



Figure III.3. A set of several pen types

Several functions can be identified. For the use case, the following selection is sufficient. Fo is the main function (purpose of the product) divided into four sub-functions. This functional framework, which is used throughout all examples, is illustrated in Figure III.4.

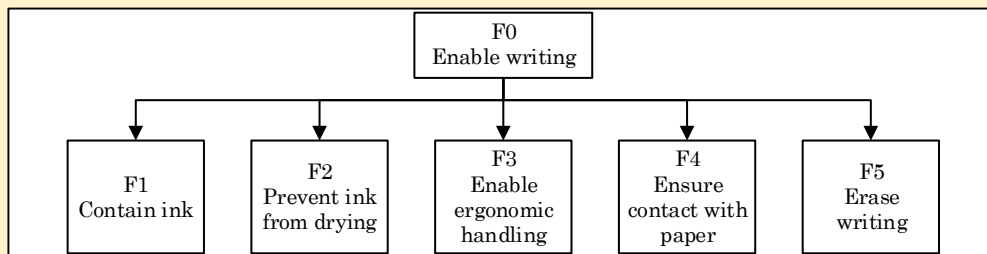


Figure III.4. Framework of technical functions for pen types

Definition III.2: Functional Subassembly

If a technical function is realised, it contains at least one component. The combination of technical function and components is called functional subassembly (FSA). The components in one FSA do not need to have mechanical links between them.

A component may be allocated to more than one technical function. Every component has to be allocated to at least one technical function. A technical function must contain at least one component. This allocation of components to technical functions can be expressed by a matrix, called **F**. This matrix shows the affiliation of all components to all technical functions as explained in equation (III.1).

$$\mathbf{F} = \begin{pmatrix} f_{11} & \cdots & f_{1j} \\ \vdots & \ddots & \vdots \\ f_{i1} & \cdots & f_{ij} \end{pmatrix} \text{ with } f_{ij} = \begin{cases} 1 & \text{if component } j \in \text{FSA } i \\ 0 & \text{else} \end{cases} \quad \forall i, j \in \mathbb{N} \tag{III.1}$$

If a technical function is not realised, i.e. its functional subassembly is not existing in a product, the according entries are all set to zero.

Example III.3: Technical Function Allocation

Combining the ball pen in Example IV.1 with the technical functions of Example IV.2, the allocation of components to technical functions may be done as follows. The technical functions become functional subassemblies.

$$FSA_1: \{5;6\} \quad FSA_2: \{1;3;4\} \quad FSA_3: \{2;3\} \quad FSA_4: \{2\} \quad FSA_5: \{\}$$

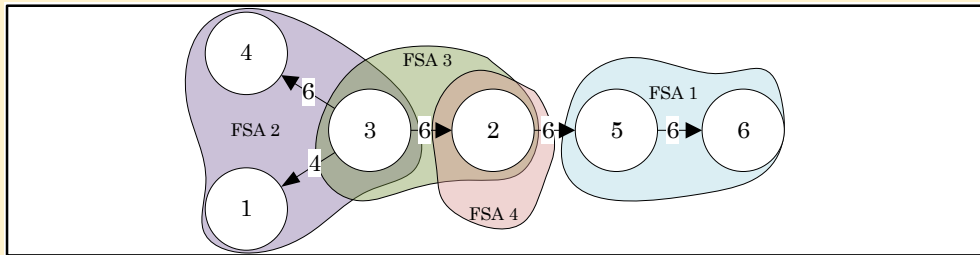


Figure III.5. Ball pen DFC with technical functions

The allocation is illustrated in Figure III.5. The matrix **F** of this example is the following:

$$F_{ex} = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

III.1.3. The physical and functional architecture

The physical and functional architecture (PHARE) is an abstraction step from the component level, based on the products’ functional subassemblies. The assembly representation is shifted from the physical DFC level to a hybrid physical and functional view: nodes in the DFC represent components and arcs their relations; whereas nodes in the PHARE represent FSA and arcs their relations.

Definition III.3: Physical and Functional Architecture (PHARE)





The PHARE is a hybrid product model. It is based on the relations of the product FSA between each other. These relations describe the product structure. It furnishes at the same time a functional and physical view of the product structure.

For each relationship between functional subassemblies, a distinct representation is defined to generate the PHARE graph representation. These representations are summarised in Table III.1. **All possible relations** between FSA can be described by five different PHARE relations: *identity*, *inclusion*, *partition*, *contact* and *separation*.

The *contact* is a relation which means that one or more components of a functional subassembly position or/and are positioned by one or more other components of one or more other functional subassemblies. It only concerns the arcs of a DFC.

The *partition* means that a functional subassembly has one or more common components with one or more other functional subassemblies.

Table III.1. PHARE relations and their symbols

Relation	Description	PHARE Symbol
Identity	It is represented by a shared node.	
Inclusion	It is represented by an aggregation link analogous to an UML aggregation.	
Partition	It is represented by a dotted line.	
Contact	It is represented by a single or bidirectional arc.	
Separation	No link exists between to nodes.	

The *inclusion* signifies that a functional subassembly contains at least one another. This means, all the components of an included functional subassembly are at the same time part of the functional subassembly which is including.

Finally, an *identity* means that a functional subassembly has the same components in common with one or more of the other functional subassemblies. Per definition, this relationship is also covered by inclusion but represents a more constrained case. The information if two functions are performed by exactly the same components or not is very interesting for the analysis of a product.

The *separation* means that a functional subassembly does not have any common components with other functional subassemblies. This relation is mentioned because in the similarity analysis presented later on, not only existing relations are taken into consideration but also common separations.

The PHARE model and its graph can be represented mathematically in a matrix, called **P**, where each relation type has its distinct entry. It shows all relations between all functional subassemblies which are defined in the technical function referential. If a technical function is not realised, its entries in the matrix are all set to zero. Matrix **P** is defined in equation (III.2). Use cases which are based on the matrix representation of the PHARE are introduced in the following chapter.

$$\mathbf{P} = \begin{pmatrix} p_{11} & \cdots & p_{1j} \\ \vdots & \ddots & \vdots \\ p_{i1} & \cdots & p_{ij} \end{pmatrix} \text{ with } p_{ij} = \begin{cases} 4 \text{ if identity} \\ 3 \text{ if entering inclusion} \\ -3 \text{ if leaving inclusion} \\ 2 \text{ if partition} \\ 1 \text{ if entering contact} \\ -1 \text{ if leaving contact} \\ 0 \text{ if separation} \end{cases} \quad \forall i, j \in \mathbb{N} \quad (\text{III.2})$$

The above-mentioned relations do not have an equal priority, rather there is a hierarchy which impacts the manner how the PHARE graph is built. The relations are divided into primary relations and secondary relations, based on the interweaving of their interactions. Primary relations are more important in terms of interconnections than secondary relations and strong relations are more important than weak relations. For this reason, the values for the different relations in matrix **P** differ. As all of the relations are considered equally different (none of them is very much more important than the others), the distances in the scale are chosen equally. And therefore the applied scale reaches from zero to four. Furthermore, this hierarchy, illustrated in Figure III.6, is important for the design analysis later.

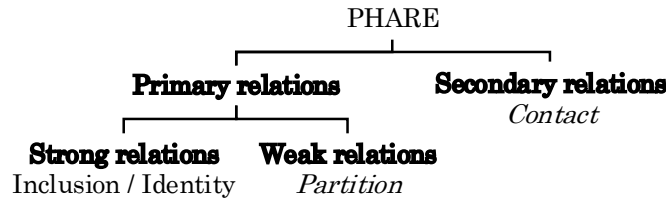


Figure III.6. Hierarchy of PHARE relations

For the PHARE generation the set of five constraints described below have to be respected:

- (n°1) Two FSA can be connected by only one relation. Multiple relations between the same FSA are not allowed except the case described in (5).
- (n°2) Primary relations are a prior to secondary relations, i.e. if there is a primary relation between two FSA, a secondary relation is not established to reduce the number of relations.
- (n°3) The inclusion relations are transitive: if $A \in B$ and $B \in C$, then $A \in C$. In this case, no link must be added between A and C.
- (n°4) If there is an inclusion relationship $A \in B$, all incoming and outgoing links are to relate to A except the ones in B but not in A. In this case the links of this element are kept as they meet the other constraints.
- (n°5) If contacts exist in both directions between two FSA, the direction with the higher number of contacts dominates and is represented in the PHARE. If the number of contacts is identical, then the direction of the contact with the highest number of DOF eliminated is selected. In case of equality, a contact in both directions is generated. It is counted as entering contact for both FSA.

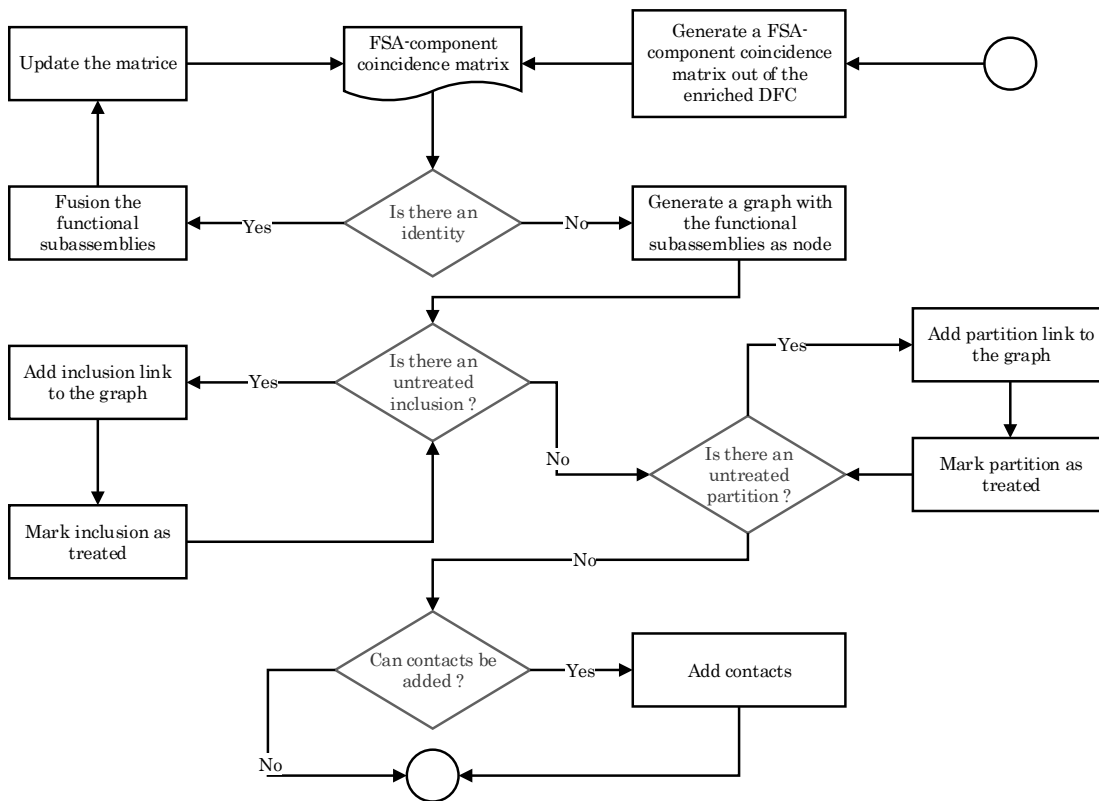


Figure III.7. Generation process for the PHARE graph representation

The generation process for the PHARE graph representation follows the order described in Figure III.7. For the matrix generation, the fusion of identical FSA is not necessary. It can be seen that strong primary relations have priority in regard of weak primary relations. And secondary relations are added at last.

An illustrative comparison between the DFC representation and the PHARE representation is furnished by Figure III.8. It illustrates with help of the FSA 'a' and 'b' and the components 1-3 the appearance of PHARE relations in DFC, the PHARE graph and its matrix.

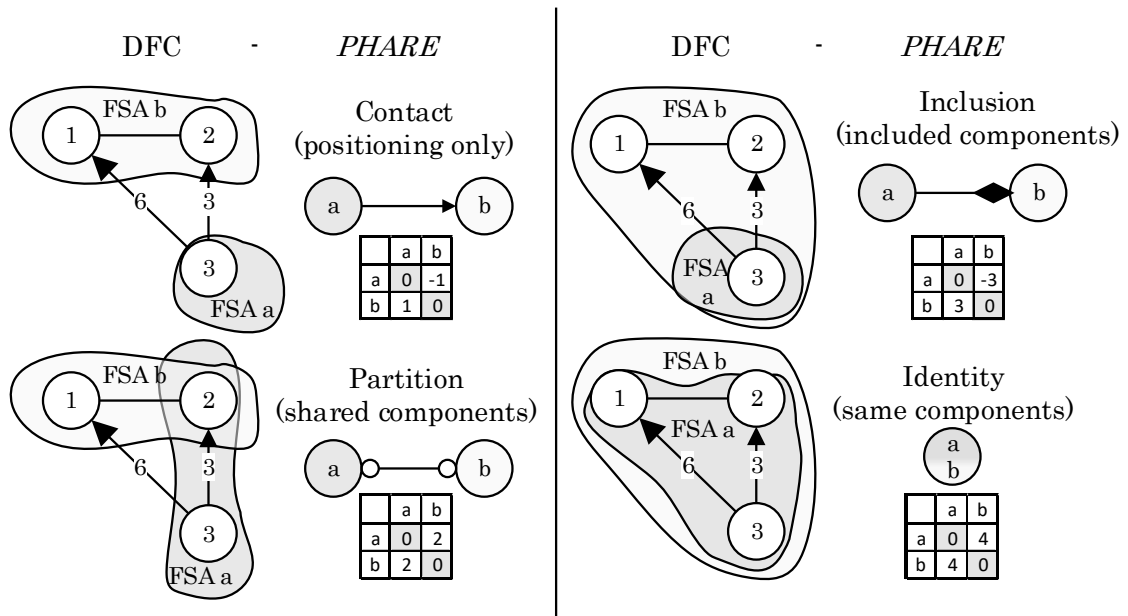


Figure III.8. The four relations in PHARE representation (graph and matrix)

As noted each relation has its distinct entry in the matrix where directions are indicated with positive or negative numbers. This concerns the relations *contact* and *inclusion* which are counted positively when entering an FSA and negatively when leaving an FSA. Whereas the relations *identity* and *partition* are undirected and only counted positively. If no relation exists between two FSA, the according matrix entry is set to zero. The shift of the representation from a component based view to the hybrid physical and functional view becomes obvious in the direct comparison.

Example III.4: PHARE generation

The PHARE relations are identified in the DFC with FSA (Figure III.9) which has been defined in the previous example.

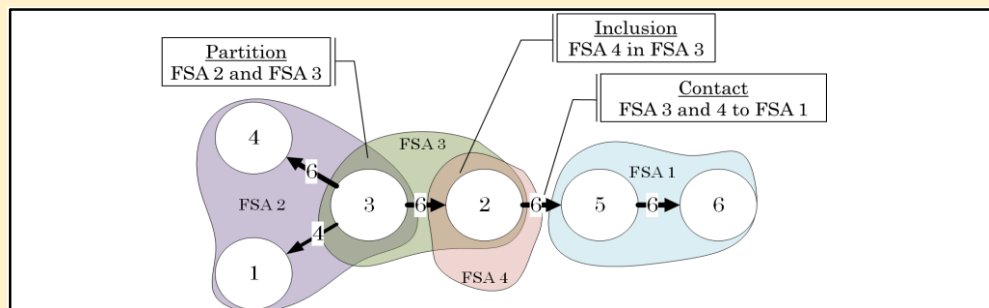


Figure III.9. Example of PHARE relations in DFC

The component oriented DFC model is now shifted to the hybrid PHARE model. The nodes represent no longer components but functional subassemblies. The arcs are added according to the definitions given previously.

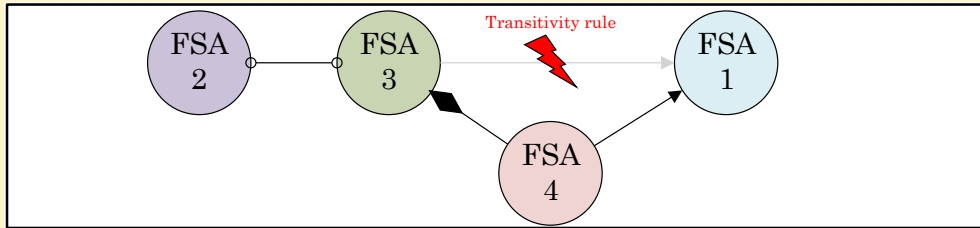


Figure III.10. PHARE example

The relations are the following: *partition* between FSA 2 and FSA 3, *inclusion* of FSA 4 in FSA 3 and *contact* from FSA 4 to FSA 1 and FSA 3 to FSA 1. However, as FSA 4 is included to FSA 3, the transitivity rule is applied (n°4): only the *contact* from FSA 4 to FSA 1 is considered.

The PHARE representation is expressed mathematically in the matrix below. Its size is 5x5 as five technical functions are defined in the framework.

$$P_{bp} = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 3 & 0 \\ -1 & 0 & -3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

The lines and columns represent the FSA in increasing order (first line/column for FSA 1, second line/column for FSA 2, ...). The entries related to technical function five are set to zero as it is not realised in the product examined.

III.1.4. Function design analysis

Beside the use of the PHARE for product similarity analysis which is detailed in the following chapter, it features in a first step as well the identification of the functional design of different products. It highlights the coupling or uncoupling of functional subassemblies.

Two strategies can be highlighted and supported. On one hand, the strategy of function separation is identified with *contact* relations. A PHARE model containing only *contact* relations means that all functions are uncoupled in the architecture. The PHARE matrix, analogous to the matrix of design parameters and functional requirements of the axiomatic design theory [Suh 2001], helps to visualise the coupling and uncoupling. However, the mapping of design parameters to functional requirements in axiomatic is not directly on the level of product architecture as it takes into account the effect of a component group on the functional requirement. Whereas the PHARE analyses the architectural implications of “functional requirements” (the FSA) by their “design parameters” (components into the FSA). The integration of functions is expressed by the relation types *inclusion* and *identity*. Identity means that two different technical functions are realised by exactly the same components, *inclusion* means that a part of the components belonging to one technical function realise at the same time another technical function. The relation type *partition* does not correspond to one of the two strategies and should be avoided if designing following these strategies.

Thus, product design can be analysed with the PHARE model in regard of one of these design strategies and functional subassemblies which have to be improved can be identified.

Another benefit, as illustrated by the example, is the identification of “independent” parts of product design, having only entering *contact* relations. This is an indicator for product variety management, because these parts can either be optional when they not fulfil an essential technical function, or they can be issue to easy variations. Therefore, PHARE supports the identification of parts of the product which should be standardised (the parts where FSA are highly coupled) and of parts which can be varied to be able to propose product variations.

Example III.5: Functional design analysis of a ball pen

With the PHARE representation, the ball pen can be analysed in regard of the coupling of its technical functions. Figure III.11 illustrates the PHARE, functional subassemblies and product design of the ball pen.

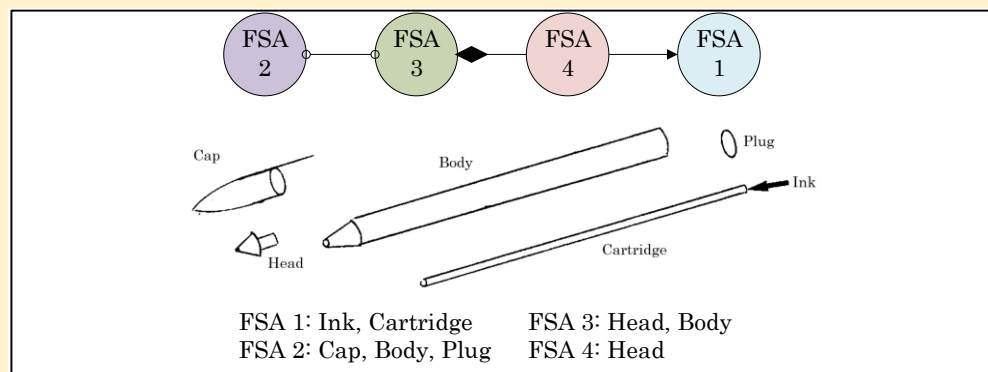


Figure III.11. Analysis of a ball pen design

It is neither following the strategy of function coupling, nor the strategy of uncoupled functions. FSA 1 can be identified as uncoupled from the rest of the product. This has two possible consequences for design: FSA 1 could be an optional function if it is not essential for the purpose of the product. Or, it can be a varying part of the product, the only constraint to meet is the interface with FSA4. The last point is making sense in reality as the cartridges can be changed to change writing colours (“reconfiguration” of the ball pen).

III.2. Enabling assembly comparison

This paragraph addresses the research questions belonging to Aim 1.2. The literature review has emphasised the need for a taxonomy and classification of assembly technologies which is common for the presented research work. Present work is very varying and wide-spread, and not oriented to furnish an assembly technology framework for use in product modelling. The new taxonomy and classification has to ensure a common, consistent vocabulary and the compatibility of assembly information with the product model and the use of these model. After the definitions, a tool to gather assembly information in a consistent way out of industrial practise is presented. Finally, the integration of assembly knowledge, based on the taxonomy, to the product model is presented. The objective is to enable the comparison of used assembly technologies and operations over several products.

III.2.1. Taxonomy and classification of assembly technologies

The taxonomy gives a frame for the classification and definition of assembly process related elements. The frame ensures the compatibility with the presented models. The aim is also to formalise and structure the data to ease their use. A classification is proposed which is used for examples and use cases later on. The data structure of assembly knowledge with its link to the product model is available in Appendix A.

III.2.1.1. Taxonomy

The new taxonomy is based on the following hypothesis which distinguishes the assembly process domain into distinct parts:

- On the one hand, there are operations intervening directly for the realisation of a mechanical link. Thus, these operations are the ones which realise the connection of two components. They are called *assembly operations*.
- On the other hand, there are operations which do not realise mechanical links but which contribute to the quality of the product. These operations do not realise the connection of two components but the conditioning of the components or the connection. They are called *complementary operations*.

In the following, the characteristics of assembly operations are defined, also in view of their application to the product model.

Definition III.4: Assembly Operation

An *assembly operation* is an operation which realises a mechanical link. One *assembly operation* is used to realise one mechanical link. The same type of *assembly operation* can be used throughout an assembly to realise different mechanical links. An *assembly operation* is defined throughout its associated assembly parameters.

Analogous to assembly operations, complementary operations are defined. They are strongly linked to assembly operations. Only if an assembly operation exists, a complementary operation can be defined, because the assembly operations realises the mechanical link on whom the complementary operation refers to.

Definition III.5: Complementary Operations

A *complementary operation* is an operation which realises a mechanical link. One or more *complementary operations* may be used around one mechanical link. The same type of *complementary operation* can be used throughout an assembly. *Complementary operations* are associated to the assembly operation of its according mechanical link by precedence information (before or after assembly operation). A *complementary operation* is defined throughout its associated assembly parameters.

The level of complementary and assembly operations is very detailed. Its selection restrains the assembly process to one precise operation with its according parameters. When applying the approach to products being developed, a more generic category leaves flexibility for the designer to define first the assembly category and to choose later on the precise assembly operations and parameters. For example, it is easier to define in a first step that a mechanical link with welding technology than choosing one specific with parameters. Also, an assembly comparison on the level of assembly and complementary operations is too precise in product variety. It risks to give similar results as the Boolean comparison which is to be avoided.

In consequence, two new domains are introduced, regrouping the detailed assembly and complementary operations: the domain of assembly operations realising mechanical links is called *assembly technology*. And the domain of the other operations is called *link attributes*. Therefore, the elementary components of *assembly technologies* are *assembly operations*. The elementary components of *link attributes* are *complementary operations*. Both, assembly technology and link attributes are defined as follows.

Definition III.6: Assembly Technology and Link Attribute

Assembly technology is a term regrouping assembly operations. It is a more generic granularity level which permits to choose later on the detailed operation. For example: technology = welding; operation = ultrasonic welding.

The same is for *link attribute*. It gathers complementary operations. For example: link attribute = control; complementary operation = control component presence.

To sum up, an assembly process is divided into two distinct domains for assembly similarity evaluation: the domain of assembly technology and the domain of link attributes. The elementary items belonging to the domain of assembly technologies are assembly operations. And the elementary items belonging to the domain of link attributes are complementary operations.

As the aim of the research is not only to evaluate similarity but also to connect product and process evaluation for production system design, the information gathered up to now, although sufficient for a similarity analysis, is not enough to be able to generate assembly plans or sequences later on. More detailed information is needed: discriminant parameters which give the information if the parameter range of two operations is compatible. And operation parameters which are needed to fully describe an assembly or complementary operation.

Definition III.7: Discriminant Parameter

Discriminant parameters define crucial criteria of an assembly operation in regard if this operation can be regrouped with others. They represent boundary values which have to be respected by other operations when regrouping. *Discriminant parameters* determine therefore if an operation can be regrouped with another one.

In opposite to discriminant parameters, operation parameters define all parameters which have to be set to assure that the assembly operation is conducted in good terms. An operation parameter can be a discriminant parameter but does not need to be.

Definition III.8: Assembly Operation Parameter

The *operation parameter* are all parameters which have to be set and/or monitored to ensure that the assembly operation is done well. *Operation parameters* can be discriminant parameters at the same time.

Based on these information, the taxonomy is built. It is represented in Figure III.12. The domain of an assembly process is split up into assembly technology on the left side and link attribute at the right side. Both represent a domain of operations: assembly technology is linked to assembly operations and link attributes are linked to complementary operations. The detailed parameters are defined for both types of operations. The knowledge which discriminant and operational parameters are available for the different assembly and complementary operations is furnished in Appendix B.

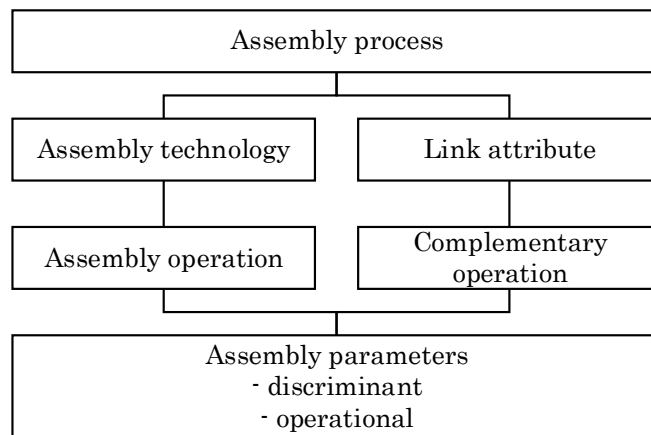


Figure III.12. Assembly taxonomy

The next step consists of classifying the information items, i.e. to assign the vocabulary to the categories defined in taxonomy, and to define a rule set connecting the domains and items.

III.2.1.2. Classification

The previous section introduced the taxonomy of assembly. The categories and their hierarchy have been defined. The framework has to be filled with information. In this way, a consistent assembly vocabulary dictionary is built to homogenise the used vocabulary. The starting point has been the DIN 8593 series. Its information has been modified and additional information has been added in strong cooperation with the industrial partner to be as close as possible to industrial practise.

To be adaptable to any use case, the vocabulary which is proposed below may be adapted by adding, changing or removing entries as long as it conforms to the defined taxonomy. The entries have to be validated before applying them to the product model to ensure the consistency of the models.

Classification of assembly technologies:

{placing-charging (PC); filling (F); press-fitting and plaiting (PP); bolted assembly and screwing (BA); plastic deformation-seaming-folding (PS); riveting (R), welding-brazing (W), adhesive bonding (AB), clipping (C), marking¹ (M)}

Classification of link attributes:

{control (c); greasing (g); marking² (m); thermal treatment (t); cleaning (cl); straightening (st); coding (co); calibrating (ca); running in (r); seaming (s)}

Classification of assembly operations:

{(to) set; (to) introduce; (to) interlink; (to) hang up; (to) fill; (to) press fit with force; (to) press fit without force; (to) nail; (to) screw; (to) seam; (to) mould; (to) engrave; (to) mark; (to) clip; (to) gas weld; (to) arc weld; (to) plasma weld;

¹ component graving

² marking a link

{(to) laser weld; (to) weld by electron beam; (to) weld by electric arc; (to) ultrasound weld; (to) friction weld; (to) braze; (to) glue; (to) rivet}

Classification of complementary operations:

{(to) mark; (to) measure forces; (to) measure torque; (to) measure power; (to) measure stiffness; (to) to measure distance; (to) measure swing; (to) measure velocity; (to) measure cone; (to) measure angle; (to) measure noise; (to) control coding; (to) heat; (to) cool; (to) clean; (to) run in; (to) straighten; (to) read code; (to) write code; (to) calibrate; (to) seam}

Assembly Operation Parameters:

{component presence; pressure; number-weight; force; position; torque; angle³; distance; noise; velocity; time; voltage; acceleration⁴}

Discriminant Parameters:

{force; pressure; volume-width; torque; frequency; number-weight; precision; angular position; lateral position; temperature; power; noise level; security}

In addition to these entries, for all assembly operations it has been determined how many degrees of freedom are eliminated by each of them, what assembly kinematics are required and, when analysing a product, which orientation in the coordinate system is used. A complete overview of the used classification and the links between the technology, operation and parameter level is joined in Appendix B.

It should be noted that several assembly operations appear for more than one technology. For example, the operation *(to) interlink* is attached to the technology *placing-charging*, as well as to the technology *riveting*. The latter because the realisation of riveting consists of interlinking the rivet with the component and riveting which means deform the rivet.

III.2.2. Template for assembly information collection

For industrial application, a detailed assembly information template is introduced in this subsection which consists of eight categories, linked by a rule set and compatibility information (Appendix B). It aims to cover the common assembly technologies with their respective operations and parameters. The tool enables the consistent gathering of information over a time span and for a multitude of products. Information is added to eight categories which represent the elements of the assembly taxonomy plus clamping requirements.

The process of assembly information selection is described in Figure III.13. The process is the connecting element between the models, taxonomy and classification introduced previously and the template illustrated in Figure III.14. The work on the taxonomy and the classifications is necessary to formalise the assembly information language with the aim to enable a consistent information gathering. Out of this defined framework, the appropriate assembly information item is selected and entered into the information gathering template. The assembly analysis can either be based on product information (i.e. technical drawings and CAD files) or assembly process files (assembly plans).

³ number of spins and final position (e.g. 540° = 1,5 spins)

⁴ in acoustics: vibration modes

The former is used when analysing new products for whom the assembly plan has not been established yet. The latter is used when analysing a product which is already in production.

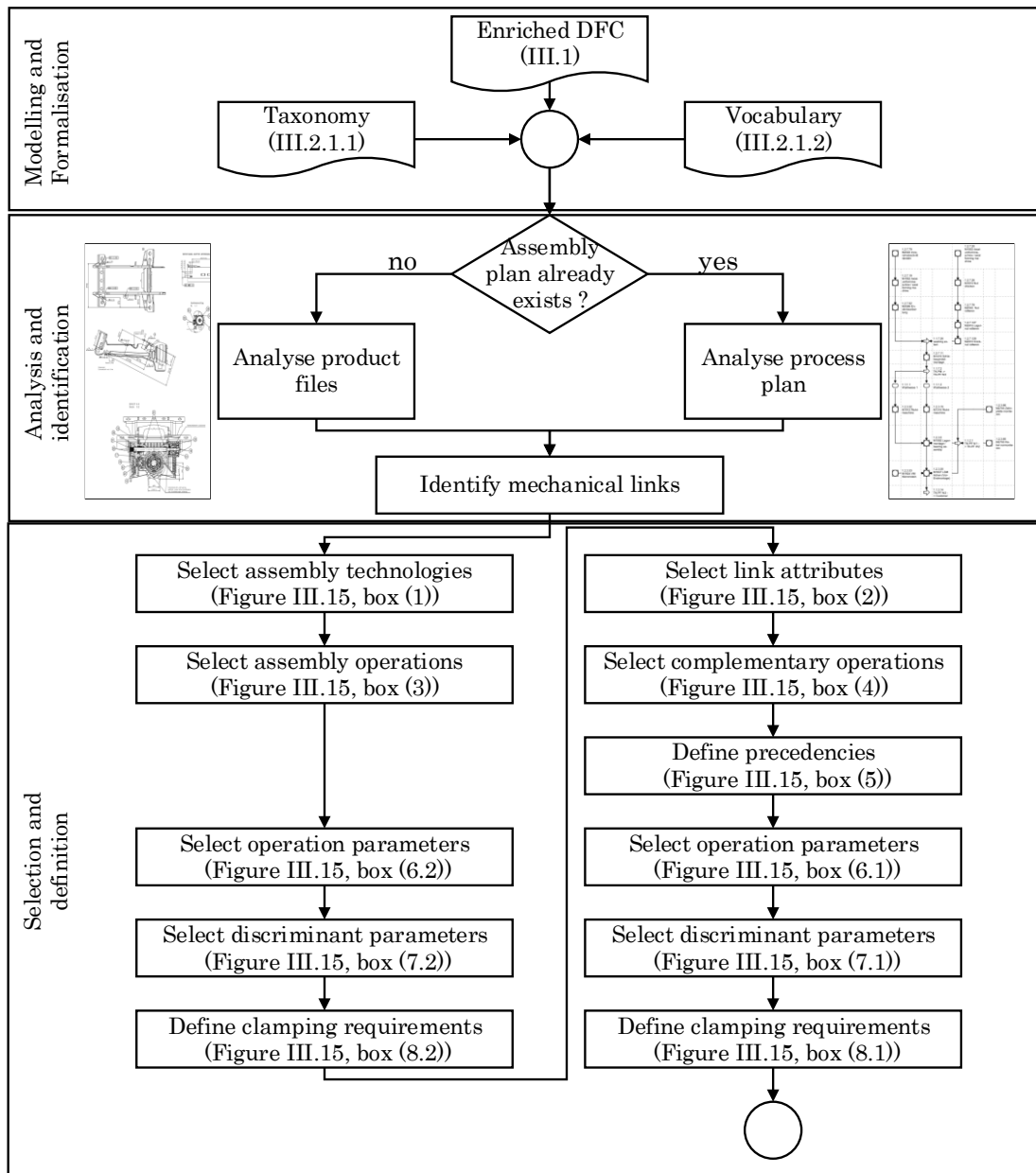


Figure III.13. Assembly information selection process

For data insertion, the sequences indicated by the arcs should be respected. In general, information about assembly technology is added before information on link attributes. So, the selection part starts with assembly technologies and the related information as for each mechanical link one assembly technology must be selected. After the assembly technologies, link attributes with their related information are selected. As defined, a mechanical link can have one or more link attributes.

In the following, the relations between the eight categories are explained. The explanation refers to the numbers from (1) to (8) as indicated in Figure III.14. The dashed lined arc details the insertion order for assembly technology related information and represent the left hand part in Figure III.13.

The dotted lined arc indicates the insertion order for link attribute related information and represents the right hand part in Figure III.13. The classifications and the vocabulary which have been defined must be respected to assure consistency.

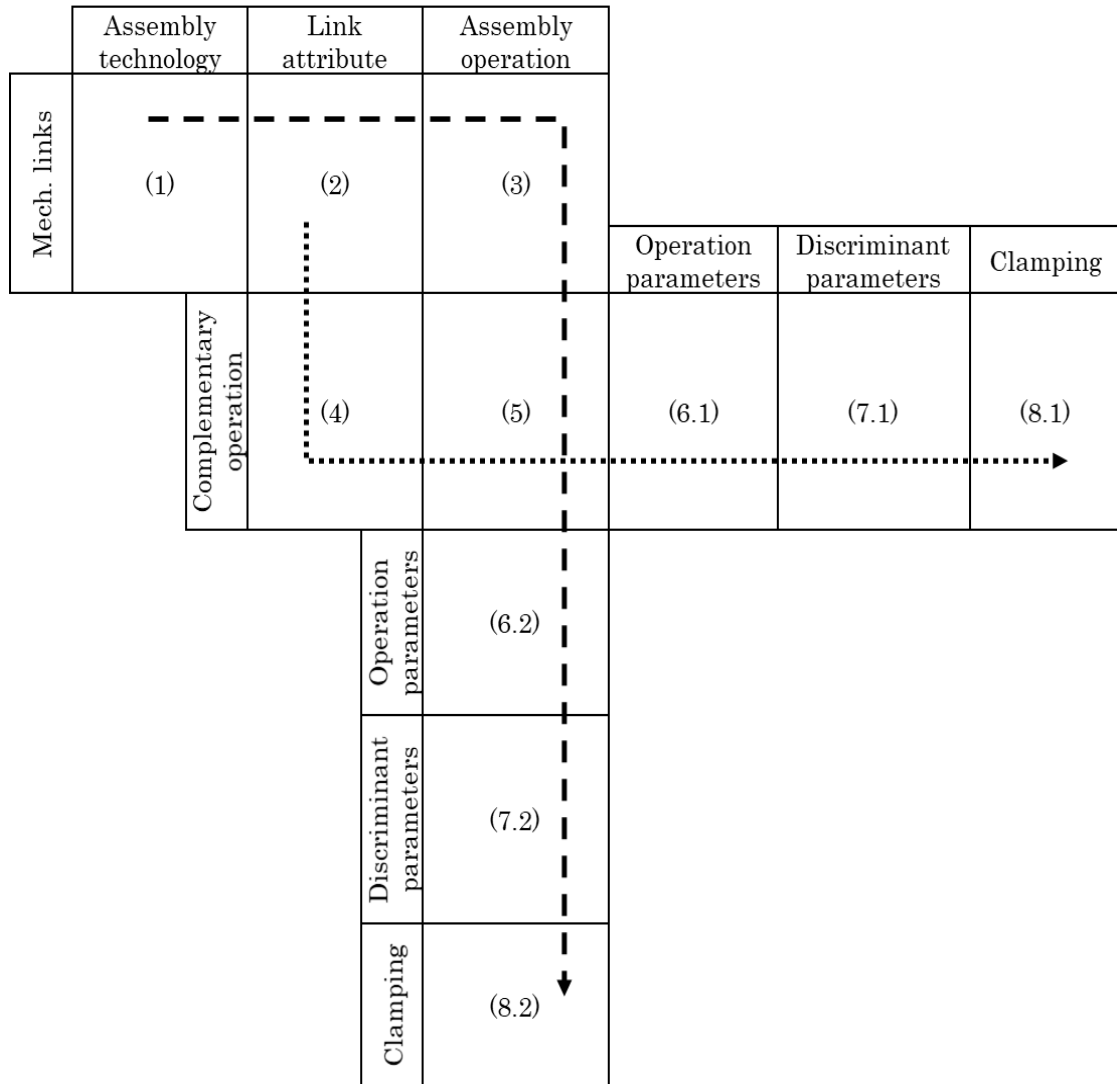


Figure III.14. Generic template for assembly information gathering

Box (1) indicates the assembly technology which is chosen to realise a mechanical link. It describes which technology is used to realise a mechanical link in an assembly, i.e. the realisation of a connection between two or more components of a product. The assembly solutions are named with nouns in the table (see also definition IV.6). For example, the assembly technology can be “screwing”.

Box (2) indicates the link attribute (one or more) which is chosen to realise a mechanical link (see also definition IV.6). It represents an additional technology which is applied to one or more components involved in a mechanical assembly, in addition to the assembly technology. Link attributes group all technologies which are needed to assure that the mechanical link is well-established and satisfies the requirements. The link attribute is named with nouns in the table. For example, a link attribute coming along with the assembly technology “screwing” could be “marking”.

Box (3) indicates the chosen assembly operation which is allowed by the assembly technologies. It describes the technical operation which is needed to perform an assembly technology on the mechanical link (see also definition IV.4). As the operations are activities, the operations have to be named with verbs.

For example, the assembly technology “screwing” allows to select one of the assembly operations “(to) screw”, “(to) introduce”, “(to) interlink” and “(to) set”.

Box number (4) details which complementary operation belongs to the link attribute (see also definition IV.5). It is a supporting operation which is not necessarily needed to realise an assembly technology, but which is a preliminary or final operation with the aim to assure the high quality of a mechanical link. It is named with verbs. Following our example, the link attribute “thermal treatment” allows the selection of the complementary operations “(to) heat” and “(to) cool”.

Box (5) is the intersection between complementary operations and assembly operations. It details their precedence relations. For example, the complementary operations “heating” and “cooling” should be realised before their respective assembly operations, whereas control operations are normally realised after the assembly. Precedencies are expressed with A (after) and B (before), from the point of view of complementary operations, i.e. complementary operation after/before assembly operation.

Boxes (6.1/6.2) *Assembly Operation Parameter*: The assembly operation parameter is one or more descriptive parameter which details the assembly operation as for example forces, torques, or pressure. For more detail, information about kinematics, orientations and eliminated DOF is added to the operation parameters. Each parameter should be quantified if possible. The parameter is named with a noun and the value can be numerical or textual. Numerical values can be zero. For example, an assembly operation parameter for the assembly operation “to screw” can be “torque 5Nm”. And an assembly parameter for the complementary operation “to heat” can be “temperature 120°C”.

In boxes (7.1/7.2) discriminant parameters for the assembly operations are indicated (if existing). The discriminant parameter (see also definition IV.8) registers the extreme values, minimum and maximum, of each assembly and complementary operation. They are complementary to the assembly operation parameters and it can be that the discriminant parameter is not an assembly operation parameter as for example the parameter “security”. The min-max interval helps later to define the compatibility of similar assembly operations. The discriminant parameter is named with a noun and its values are numerical intervals. For example, the discriminant parameter interval for the assembly operation “to screw” can be “torque [0; 5] Nm”.

Boxes (8.1/8.2) gather requirements for clamping (see also definition III.4 for *clamping*). These requirements are deduced from the operation parameters as clamping requirements are strongly linked to assembly operation parameters. If this parameter is representing a force, a torque or a movement, it is at the same time a clamping requirement. The concerned assembly parameter nouns and values are copied to the fixture requirement category. A fixturing requirement for the assembly operation “to screw” is “torque 5Nm” which means that the clamping has to resist to a torque force of at least 5Nm.

Example III.6: Assembly information template

To give an example about how to fill in the assembly information template, all information which has been defined in example IV.5 is entered. Some assumptions are done to illustrate the entries with values. The link numbers are indicated on the left hand side.

		placing changing	filling	press-fitting and plaiting	bolted assembly and screwing	...	control	seam	clean	...	(to) introduce	(to) fill	(to) press fit without force	(to) press fit without force	(to) screw
3-1	X										X				
3-4			X				X					X			
3-2				X				X							
2-5			X										X		
5-6	X						X	X						X	
		Assembly technology				Link attribute				Assembly operations					
		Complementary													
		(to) control presence filling				X				A					
		(to) clean								B					
		(to) clean				X				A					
		(to) seam				X				A					
		Operation parameters													
		component presence				X									
		pressure				0,5									
		number-weight				10g									
		force													
		position				X X X									
		torque								1Nm					
		angle								360					
		...													
		DOF				DOF eliminated				3 6 5 5 6					
						1D				+x -x -x -x +x					
						2D									
						3D									
						Linear				X X					
						Rotational									
						Complex									
		Discriminant parameters													
		torque								X					
		frequency													
		number-weight				10g									
		precision				0.1 0.1									
		angular position								360					
		linear position				X				X X					
		...													

Figure III.15. Example of assembly information template

The table shows that all over nine operations (assembly and complementary) have to be realised to assemble the ball pen previously defined. The complementary operation (to) clean appears two times as it concerns two different mechanical links. Clamping information has not been added for better readability of the table. One may add clamping for the operations needing forces as press fit and screw.

III.2.3. Integration of assembly knowledge on the product model

The information about assembly technology and link attributes is added on the arcs of the DFC product model. The reason why the DFC model is used is that it is the component-relation model. And assembly process information as presented is on the component-relation level.

To ease the representation of assembly information, two conventions are introduced. First, the arcs of the DFC are coloured with a colour which is specific for each assembly technology. And second, abbreviations are defined for each assembly technology and link attribute. These are described in the section before (classification).

Example III.7: Assembly information in the DFC model

This example refers to the ball pen model used previously. The product and its DFC are reminded in Figure III.16.

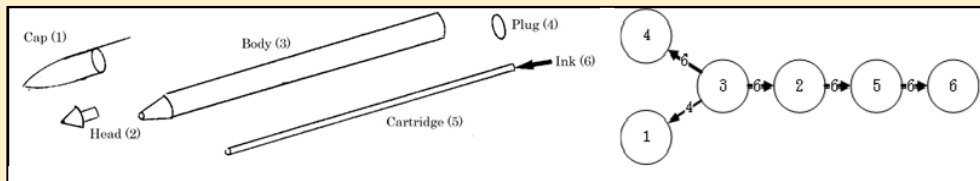


Figure III.16. Ball pen and its DFC

Concerning the used assembly technologies, the following assumptions are done:

- >> Link (3,1): placing-charging (PC); colour **green**
- >> Link (3,4): press-fitting and plaiting (PP); colour **orange**
- >> Link (3,2): bolted assembly and screwing (BA); colour **red**
- >> Link (2,5): press-fitting and plaiting (PP); colour **orange**
- >> Link (5,6): filling (F); colour **pink**

To illustrate the use of link attributes in addition to assembly technologies, the following ones can be considered:

- >> Link (5,6): control (c) the filling and clean (cl) the cartridge after filling
- >> Link (3,4): seam (s) plug after press-fitting
- >> Link (3,2): clean (cl) body and head before screwing the head

This information is now added to the DFC:

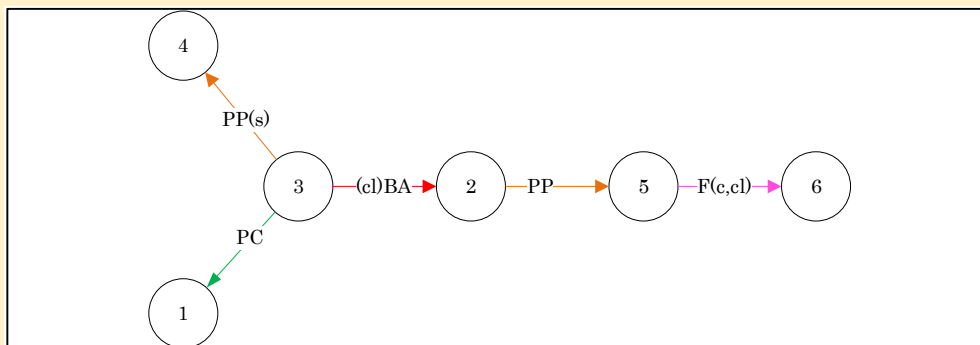


Figure III.17. DFC with assembly information

The information about eliminated DOF has not been added to the figure for better readability but it is still existing in the model. In addition, it is intrinsically linked to assembly technology and link attributes.

Furthermore, a notation convention is added to distinguish between assembly technology and link attribute: link attributes are marked in lowercase letters, regrouped in brackets. Assembly technologies are marked in capital letters. The positioning of link attributes in regard of the assembly technology gives an idea about the precedencies.

It can be noted, that, for instance, assembly information is not yet linked to technical function information. Both steps, the addition of FSA to DFC and the addition of assembly information to DFC are independent from each other.

III.3. Conclusions of the chapter

The objective to whom this chapter is dedicated, and which is identified in the research questions, is framed by the following two research aims:

- Aim 1.1: Enable the structural comparison of a product family
- Aim 1.2: Enable the assembly comparison of a product family

Concerning Aim 1.1, it has been stated that none of the classical models enables product family comparison under product variety. Amongst the examined approaches, DFC has been identified as starting point for the development of a new product model, the physical and functional architecture (PHARE). To do so, two adaptations have been done to the DFC: the definition of arc thickness in relation to degrees of freedom eliminated and, more important, the integration of technical functions via functional subassemblies (FSA) to the model. Based on the FSA, the PHARE is generated. The PHARE representation is based on the definition of a technical function framework which is unvarying for all examined products. Product variety is expressed in the PHARE by different relations between the functional subassemblies. Thus, the PHARE representation is effectively adapted for the modelling of a product variety due to the referential of technical functions which is unvarying for all examined products. It has been successfully applied to the modelling and the analysis of eleven different complex products of our industrial partner. Therefore, the requirements to the structural product modelling part, as defined in the beginning, are fulfilled.

However, despite its flexibility, the PHARE method is restricted by the technical function referential. This means that it is adapted to compare a product variety which refers to the same set of technical functions, which is, in general, a specific product domain. But the main weaknesses of the modelling approach are linked to the definition of the basic elements: DFC, technical function referential and allocation of functional subassemblies. For the generation of these three elements, the intervention of a human operator is necessary. If different operators are assigned to this tasks, there is a non-trivial risk that different interpretations may introduce incoherencies in the models.

To minimise modelling errors during the generation of the enriched DFC and PHARE, a Python software prototype has been developed in the context of the industrial chair. Via a user interface, it permits the upload of the product part list, the generation of DFC links and the allocation of components to a predefined set of technical functions. This prototype is operational and has been overhanded to the industrial partner. To minimise the risk of inconsistent entries, a connection of the software tool with a database storing knowledge about already modelled products could be useful, to allow a return of experience between products and operators. During the application in the partner company, it has been revealed that modelling products in the enriched DFC and the introduction of the PHARE reasoning itself need time and educational support at least in the beginning as it is not a common practise in the company.

On the side of academic research on design and design methods, there are two approaches which seem at a first glance similar to the developed PHARE approach.

First, it is the axiomatic design approach which takes also into account the link between functions and their realisation by the product design [Suh 2001]. However, the comparison level is not the same: axiomatic design analyses the effect, i.e. an action-reaction reasoning, of product design on functional requirements. The PHARE displays the structural and mechanical imbrication of functional subassemblies and is therefore more physical assembly oriented than effect oriented. A remaining question that might be discussed more in detail during further research work is how can coupled and uncoupled design be identified with the PHARE approach and what are the differences between axiomatic design and PHARE application from the designer's point of view.

Another approach, using matrix representations which might seem similar to the PHARE ones is the use of Design Structure Matrices (DSM). It is used to qualify and quantify interactions between product elements. Several applications and use cases are available in [Eppinger et al. 1994] and [Eppinger and Browning 2012]. However, the DSM approach is larger and more generic than the PHARE as it combines different elements in one matrix, for example the notion of risk linked with relations of product elements. The benefits of the integration of PHARE representations to DSM, i.e. using the PHARE to qualify interactions and DSM to quantify complementary information relative to the PHARE interactions may be discussed during further research.

Concerning Aim 1.2, it has been stated that no common, standardised taxonomy and classification of assembly information exist and that assembly information generally is not integrated to the product models. Common product models lack the integration of assembly knowledge and that assembly knowledge treating literature is not linked to product modelling and often manufacturing oriented (assembly = joining). To overcome this shortcoming, a taxonomy has been defined which, first, ensures that assembly information is classified consistently and which, second, formalises the link between product model and assembly information. At the same time, it gives a framework which is intrinsically flexible enough to be personalised for different use cases by changing the entries in the classification. In the outcome, the link of assembly information with the product model enables assembly comparison later on. A supplementary template for assembly information gathering has been proposed, all in consistency to the taxonomy.

By doing the link between assembly knowledge and product model, the proposed definitions are answering to the requirements which have been defined in the introduction to this chapter. During industrial cooperation, the need of a common vocabulary has been underlined and the here presented taxonomy has been successfully used for the gathering of assembly information and the discussion of assembly processes.

Although the taxonomy is thought to be a universal framework, the belonging vocabulary which is presented and used in this research work is far not exhaustive. The focus has been put on the knowledge needed to conduct the industrial case studies. This means, the vocabulary is supposed to vary from company to company and when changing the company or use cases, efforts are needed to verify and complete the assembly knowledge as it is specific to each company. In addition, the link to the product model could only be made on the level of the enriched DFC representation, as assembly technology knowledge is specific to the mechanical links. This means that two models are needed for complete the structural and assembly analysis of a product variety, being on different granularity levels. A fact which makes the analysis and

interpretation steps in the following chapter more difficult as the two levels have to be linked. Concerning the definition of assembly technology and link attributes in the DFC representation, difficulties have been revealed concerning a consistent data input. This concerns especially the technologies riveting and bolted assembly as they may concern a set of components and the decision, which components are included by these assembly types is not always evident. The same is for the placement of link attributes as for example greasing, which can be realised after an assembly operation or before the next assembly step. To avoid ambiguities or inconsistent input, a convention should be fixed. Similarly, the question where to insert control link attributes may be difficult to resolve in function of the complexity of the concerned subassembly.

The presented aspects of assembly information have been integrated to the Python software prototype developed for the enriched DFC and PHARE model. The advantage of this integration is that the assembly information is entered at the same time as the product model. This means, when defining the relations between components for DFC modelling, information about assembly technology and link attribute is entered immediately. A link to CAD software, even if difficult to realise could support the automatic extraction of assembly technology information.

To sum up, two new complementary product models have been introduced in this chapter to answer to the research question. Both are based on the DFC representation, one is dedicated to the structural analysis, the other to assembly analysis. Their use and interplay are presented in the following chapters. The presented models have been tested and validated by an industrial application on eleven different complex mechanical and mechatronic products. These products are differing in component number (from 20 to 70 components), the component type (mechanic, electronic, and electric), and the number of technical functions realised (from 14 to 21). Thus the product variety has been represented by the product choices. An excerpt of these applications is available is added in Chapter 6 but under restrained access due to confidentiality issues.

Chapter IV. Enabling the generation and improvements of product families

Based on the product models, four new similarity indices are introduced for the analysis and generation of product families under product variety and information extraction for production system design. The architectural similarity indices S_1 (design oriented) and S_2 (complexity oriented) are based on the PHARE representation. The assembly technology similarity indices S_3 (for a FSA) and S_4 (for the assembly of an FSA on the product) are based on the enriched DFC model. For S_3 and S_4 , two different calculation methods are presented, one conservative one and one taking into account similarity between assembly technologies. Four different application cases are defined for the four indices: production system paradigm identification, product design analysis, product family identification and product similarity improvement for product families.

For the co-evolution and co-design of product, assembly process and assembly system, the generation of both, product families adapted for an assembly system and multi-products assembly systems for product families is of great importance. It is one of the current challenges and research topics in today's unstable market environment for manufacturing companies. Product family generation needs tools and methods to analyse the product portfolio, in terms of structural and assembly similarity. This question is addressed by research aim 2. The requirements to a similarity analysis are:

- Similarity indices are needed which consider on one hand the product architectures and which take into account on the other hand also the similarity of assembly technology choices in product design;
- Furthermore, the assembly analysis should be sensitive to variety and therefore not Boolean (exactly the same – completely different).

The literature review carried out on this subject revealed a lack of adapted similarity indices. Although a large number of indices exists in literature, the most of them lacks the integration of assembly technology similarity. And, in addition, all of them are Boolean and component based. It means, for similarity, exactly the same component is searched throughout the product architecture. This conception of similarity indices is far too rigid and not adapted to the present industrial problem with products having differing component numbers and types but similar functional structures. The new development has to meet the following requirements:

- The similarity indices must enable an affined evaluation of similarity to overcome the shortcoming of Boolean analysis;
- To respond to co-design and -evolution issues, the similarity indices must evaluate the product architecture and the assembly technologies used;
- The similarity analysis has to be applicable for product design and assembly technology improvement in sight of new production systems.

Answering these requirements, new similarity indices are developed. This development has been built from the beginning as no existing approach could be used as starting point. The indices are based on the newly developed product models which have been introduced in the previous chapter. Based on the product architecture oriented model, similarity indices for product design are developed, and based on the assembly technology oriented model, assembly similarity indices are introduced.

The first part of this chapter presents the new similarity indices: at first the structural indices, then the assembly technology indices. In the second part, four applications on product design analysis, product family generation and product design improvement are presented. All of these are also oriented towards their consequences for the production system.

IV.1. Similarity indicators for structural and assembly comparison

Four new similarity indices are introduced in the following. Two indices for structural comparison and two indices for assembly comparison. The indices for structural similarity comparison are presented in the first part of this section. And in the second part of this section, the indices for assembly similarity are introduced. For the assembly technology indices, two different ways of calculation are presented. One which delivers conservative results by considering assembly similarity when the used technologies are identic. The other being more refined, considering also intermediate assembly technology similarity.

IV.1.1. Structural similarity comparison

The structural comparison has to be able to cope with product variety. Therefore, it is based on the physical and functional architectures (PHARE) of the products, the product model which has especially been developed for this reason: to enable the product comparison of a product variety. For similarity analysis, the functional subassemblies (FSA) and their relations are compared. The two indices for structural comparison are called S_1 and S_2 and are located in the research parameter of aim 2.1.

IV.1.1.1. Calculation of structural similarity (S_1 and S_2)

The calculation of S_1 and S_2 itself is based on the matrix which represents the PHARE, called P . To remind, it represents the relations between the FSA and one matrix is generated for one product. The matrix is defined in equation (III.2).

The PHARE representation furnishes two different views on structural product similarity. On one hand, similarity can be assessed by comparing the common relation between the functional subassemblies of two products. This analysis is focused on the product design similarity as it evaluates, if the realised FSA are located similarly in the product architecture. The according index is called S_1 .

Product architecture similarity: S_1 – product design similarity

On the other hand, similarity can also be assessed by taking into account, in addition to the common existent relations, common absent relations. The consideration of common absent relations between the FSA allows to evaluate the similarity of design complexity of two products. A differing number of absent relations means that the same FSA has more imbrications to other FSA in one product than in the other. As the number of imbrications is an indicator for complexity, a differing number of imbrications means different complexity. It should be noted that the complexity similarity is evaluated and no statement is done by the similarity index if the design is complex or not. The according index is called S_2 .

Product architecture similarity: S_2 – product design complexity similarity

For a complexity analysis, one may refer to the coupling of functional subassemblies as described in Chapter III. A similarity value of S_1 and S_2 is calculated for each FSA to identify subassemblies which are similar in both products. Next, the application order is described.

- 1) Generation of the matrices representing the PHARE
- 2) Binary comparison of two matrices (for two products) and input weighting
 - a. Identification of identical elements
 - b. Identification of similar elements
- 3) Similarity assessment by functional subassembly

At first, in step 1, two different PHARE matrices are calculated according to equation (IV.1). In this mathematical description, p_{ij} are the entries of P_1 (the PHARE matrix of product one) and p_{kl} are the entries of P_2 (the PHARE matrix of product two).

The proposed approach in step 2 is a pairwise binary comparison of the entries of both PHARE matrices P_1 and P_2 by functional subassembly. During this pairwise comparison, the entries of these both matrices are combined to build a new weighted comparison matrix P^A which is the basis for similarity analysis (A stands for analysis matrix). The entries P^A , called p_{mn} , are the weighted input based on the entries of P_1 and P_2 . The building itself consists of two steps:

- a. Identification of identical elements

$$\text{If } p_{ij} = p_{kl} \text{ and } p_{ij}, p_{kl} \neq 0, \text{ then } p_{mn} = 16; \forall i = k = m, j = k = l; \forall i, j, k, l, m, n \in \mathbb{N}^6 \quad (\text{IV.2})$$

With equation (IV.2), all identical entries which are not zero are identified. These represent existent common links, necessary for the calculation of S_1 . Equation (IV.3) identifies all identical entries equal to zero. These are necessary to calculate the S_2 , as they represent common absent links. These conventions and the value of 16 is needed for weighting the entries as explained in the next step.

$$\text{If } p_{ij} = p_{kl} \text{ and } p_{ij}, p_{kl} = 0, \text{ then } p_{mn} = -16; \forall i = k = m, j = k = l; \forall i, j, k, l, m, n \in \mathbb{N}^6 \quad (\text{IV.3})$$

- b. Identification of similar elements

Equation (IV.4) calculates the weight of the entries of matrix P^A using the values defined for the distinct relations in the PHARE representation. The theoretic maximum value of the operation $p_{ij} \cdot p_{kl}$ is 16 because the maximum value defined for matrix P is four, representing identities.

$$\text{If } p_{ij} \neq p_{kl} = 0, \text{ then } p_{mn} = |p_{ij}| \cdot |p_{kl}|; \forall i = k = m, j = k = l; \forall i, j, k, l, m, n \in \mathbb{N}^6 \quad (\text{IV.4})$$

In a last step, the entries are normalised with the theoretical maximum, which is 16. Therefore, to finalise the matrix \mathbf{P}^A , according to equation (IV.5), all the entries calculated according to the equations (IV.2 – IV.4) are divided by 16.

$$\mathbf{P}^A = \begin{pmatrix} \frac{p_{11}}{16} & \dots & \frac{p_{1n}}{16} \\ \vdots & \ddots & \vdots \\ \frac{p_{m1}}{16} & \dots & \frac{p_{mn}}{16} \end{pmatrix} \forall i, j \in \mathbb{N}^2 \quad (\text{IV.5})$$

To sum it up, the identical elements representing common non-null relations have the value 1, identical elements modelling a common absent relation have the value -1 and non-identical entries belonging to the range $0 \leq x < 1$. All possible values which can occur in matrix \mathbf{P}^A are added in Table IV.1, detailing the belonging combination of PHARE relations. As the mathematical operation is a multiplication, the entries for relation 1 and relation 2 in the table can be permuted.

An entry which is *constant* means that the value is automatically set without calculations, in respect to formula (IV.2) and (IV.3). The sign of the values depends on the direction of the arcs in the PHARE. If there is no sign, the arcs are undirected.

Table IV.1. Value range for matrix \mathbf{P}^A

Comparison		Calculation	Absolute Value (a)	Normalised value ($\frac{a}{16}$)
Relation 1	Relation 2			
Identity	Identity	constant	16	1
Composition	Composition	constant	16	1
Partition	Partition	constant	16	1
Contact	Contact	constant	16	1
No link	No link	constant	-16	-1
Identity	Composition	$4 \cdot \pm 3 $	12	0,75
Composition	Composition ⁻¹ (inverse)	$3 \cdot \pm 3 $	9	0,5625
Identity	Partition	$4 \cdot 2$	8	0,5
Composition	Partition	$ \pm 3 \cdot 2$	6	0,375
Identity	Contact	$4 \cdot \pm 1 $	4	0,25
Composition	Contact	$ \pm 3 \cdot \pm 1 $	3	0,1875
Partition	Contact	$2 \cdot \pm 1 $	2	0,125
Contact	Contact ⁻¹ (inverse)	$1 \cdot \pm 1 $	1	0,0625
No link	Identity	$0 \cdot 4$	0	0
No link	Composition	$0 \cdot \pm 3 $	0	0
No link	Partition	$0 \cdot 2$	0	0
No link	Contact	$0 \cdot \pm 1 $	0	0

Figure IV.1 illustrates the calculation of the entries for \mathbf{P}^A . Regarding the contact (-1) in matrix \mathbf{P}_1 and the composition (-3) in matrix \mathbf{P}_2 , the calculation is $|-1| \cdot |-3|$ divided by 16. The result, the according entry in \mathbf{P}^A , is $3/16$ or 0,1875.

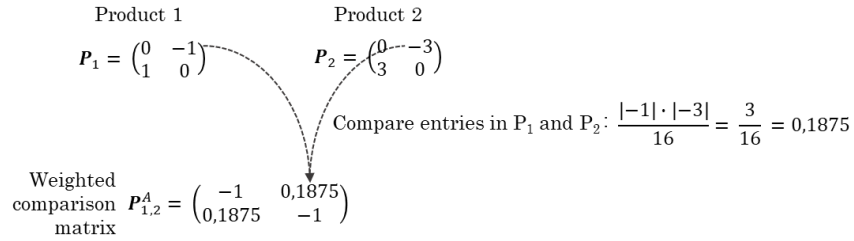


Figure IV.1. Illustration of P^A entry calculation

In step 3, based on the normalised matrix P^A , the two similarity indices can be calculated. As mentioned, S_1 considers the similarity based on existing links between functional subassemblies (see equation (IV.6)). It is calculated by matrix rows. One row represents one FSA. The sum of the row entries of a row m which are superior to zero is divided by the number of the row entries which are superior or equal to zero (one row represents one FSA). In this way it compares the weighted number of existent relations to the number of all relations which exists concerning one FSA in the two products.

$$S_1 = \frac{\sum_1^n p_{mn} \text{ for } p_{mn} > 0}{n \text{ for } p_{mn} \geq 0}; \forall m, n \in \mathbb{N}^2 \quad (\text{IV.6})$$

For example, S_1 is equal to 1 (100% similarity) if all entries are identical and equal to zero if no common relation exists.

Example IV.1: Similarity calculation for ball pen and feather pen

In this example, the calculation of the similarity indices is illustrated with comparison of the ball pen example to a feather pen. The framework of technical functions is the same as defined in Chapter III. The feather pen is introduced directly with its PHARE representation. Its complete modelling part is available in Appendix C. Both PHARE representations are illustrated in Figure IV.2.

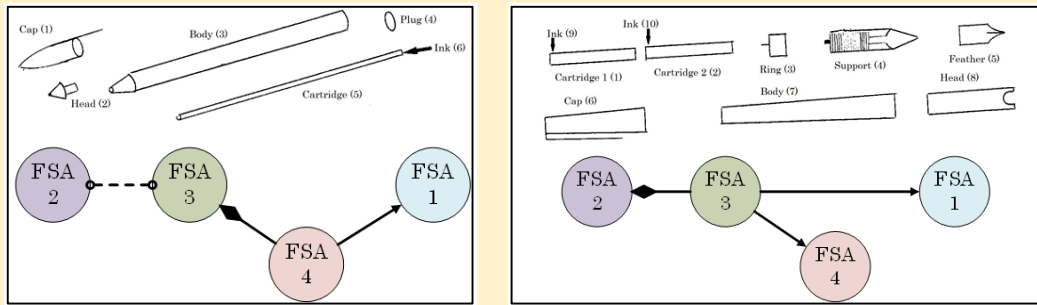


Figure IV.2. PHAREs of ball pen (left) and feather pen (right)

The PHARE matrices of the pens are the following, the FSA being in the order of the lines and columns (FSA₁ = line 1 and column 1, ...):

$$P_b = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 3 & 0 \\ -1 & 0 & -3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}; P_f = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ -1 & -3 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Out of these, the matrix P^A can be calculated:

$$P_{b,f}^A = \begin{pmatrix} -1 & -1 & 0 & 0 & -1 \\ -1 & -1 & 0,375 & -1 & -1 \\ 0 & 0,375 & -1 & 0,1875 & -1 \\ 0 & -1 & 0,1875 & -1 & -1 \\ -1 & -1 & -1 & -1 & -1 \end{pmatrix}$$

The Table IV.2 gives the similarity values calculated by functional subassembly for the pen type example. The values are expressed as percentage. To give an example of the calculations, the indices S_1 and S_2 are calculated in detail for FSA 2.

Table IV.2. Structural similarity calculation for pen types

[%]	FSA 1	FSA 2	FSA 3	FSA 4	FSA 5
S_1	0	38	19	9	0
S_2	60	88	51	64	100

$$S_1^{FSA2} = \frac{0,375}{1} \approx 38\%; S_2^{FSA2} = \frac{0,375 + |-1| + |-1| + |-1| + |-1|}{5} = \frac{4,375}{5} \approx 88\%$$

The second index, S_2 , takes also into account the absence of links in both PHARE representations. The following formula (IV.7) describes the way to calculate this index for one functional subassembly, represented by one row m .

$$S_2 = \frac{(\sum_1^n p_{mn} \text{ for } p_{mn} > 0) + (\sum_1^n |p_{mn}| \text{ for } p_{mn} = -1)}{n}; \forall m, n \in \mathbb{N}^2 \quad (IV.7)$$

It calculates the sum of all entries superior to zero plus the number of all entries equal to minus one, all divided by the number of entries. The sum of all entries superior to zero is the weighted sum of all non-null relations. The number of entries equal to -1 is the number of common absent relations. These are divided by the number of all possible relations. Consequently, S_2 evaluates common existent and absent relations for a view on complexity similarity. The range of both indices goes from zero to one.

IV.1.1.2. Interpretation of structural similarity (S_1 and S_2)

The similarity indices S_1 and S_2 are coupled. They have to be interpreted conjointly for deduction. The two indices can be interpreted in the following way:

- 100% for S_1 and 100% for S_2 : the functional subassembly (FSA) exists in both products within a similar product architecture of similar complexity;
- 0% for S_1 and 100% for S_2 : the FSA does not exist in the examined products and is, therefore, no longer considered;
- 0% for S_1 and for $S_2 < 100\%$: the FSA exists only in one of the two examined products. Or it is situated in a completely opposite way in the physical and functional architecture of the products. In both cases the FSA has to be kept in mind as important differentiating element;
- 0% < x < 100% for both indices: the domain of interpretation submitted to some uncertainty.

For the last case, three different value combinations exist:

- High S_1 and high S_2 : the products are of a similar physical-functional architecture and similar structural complexity;
- Low S_1 and low S_2 : the products have a physical-functional architecture with little similarity and a different structural complexity;
- Low S_1 and high S_2 : the products have a low physical-functional architecture similarity but, though, similar structural complexity.

The combination of high S_1 and low S_2 is not possible due to the definition of the indices. A high S_1 score induces automatically a high S_2 score. The interpretations presented above are a generic interpretation of the index values based on the way how they are calculated and the information defined in the PHARE model. Specific applications of the indices and the interpretation application on different purposes are presented in section IV.2.

The indices S_1 and S_2 take only into account the functional and physical product architecture, but they do not give any information about the assembly technologies which are used. This additional knowledge is necessary to decide the assembly system type to select.

IV.1.2. Assembly similarity comparison

The assembly comparison is based on the Datum Flow Chain (DFC) of the products which has been extended with assembly technology information. This product model has been developed for the purpose to enable the comparison of assembly technologies of a product variety. For similarity analysis, the assembly technology used by the functional subassemblies (FSA) are compared. The two indices for technology comparison are called S_3 and S_4 and are located in the domain of research aim 2.2.

IV.1.2.1. Standard assembly similarity calculation method

Index S_3 evaluates the internal similarity of each functional subassembly. It considers the assembly technologies used in the functional subassembly. That mean all mechanical links that are situated into the FSA are examined. It determines thus the way how the FSA is realised. In consequence, the similarity evaluated by S_3 is called *internal assembly similarity* in the following.

Assembly technology similarity: S_3 – assembly similarity in the FSA (internal)

Index S_4 evaluates the similarity of the assembly technologies used to assemble one FSA in regard to other ones. This means that the similarity of assembly technology is examined which concerns the links relations which one FSA has to the others. It considers all assembly technologies which are used to locate a functional subassembly, i.e. all entering arcs. In this way, the similarity of how de functional subassembly is assembled to the whole product is examined. In consequence, the similarity evaluated by S_3 is called *external assembly similarity* in the following.

Assembly technology similarity: S_4 – assembly similarity to the FSA (external)

The general approach to calculate both, internal and external assembly similarity is following five steps:

- 1) Generation of the new DFC model extended with functional subassemblies and assembly technology information on the arcs;

- 2) Selection of arcs to evaluate (internal for S₃ and entering external for S₄);
- 3) Generation of a technology matrix which contains information about technology-subassembly coincidence;
- 4) Generation of a comparison matrix for the binary comparison of two products;
- 5) Similarity calculation by functional group.

Step 1 has been described in the precedent chapter. To illustrate step 2, Figure IV.3 gives an example of a functional subassembly in a DFC with its different links and their signification. For S₃, the arcs belonging to FSA 2 and FSA 3 would be considered (here called “internal arcs”). For S₄, the entering arc to FSA 1 would be considered (“external arc”).

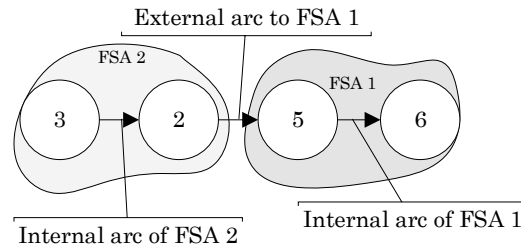


Figure IV.3. Internal and external arcs

In step 3, the assembly technology matrix \mathbf{T} is built, in which the rows represent all assembly technologies and the columns stand for the functional subassemblies. It is the technology-subassembly coincidence matrix. The entries of matrix \mathbf{T} , assigned t_{ij} , are equal to one if one technology j is used for a functional group i , and zero elsewhere. The considered technologies are identified as described in Chapter III. Two matrices \mathbf{T}^{int} and \mathbf{T}^{ext} have to be built for each product. \mathbf{T}^{int} regroups information about internal assembly technology and is used for the calculation of S₃. \mathbf{T}^{ext} considers external assembly technology and is used for the calculation of S₄.

$$\mathbf{T}^{\text{int/ext}} = \begin{pmatrix} t_{11} & \cdots & t_{1j} \\ \vdots & \ddots & \vdots \\ t_{i1} & \cdots & t_{ij} \end{pmatrix} \text{ with } t_{ij} = \begin{cases} 1 & \text{if technology } j \text{ is used in FSA } i \\ 0 & \text{else} \end{cases} \quad \forall i, j \in \mathbb{N}^2 \quad (\text{IV.8})$$

For the technology comparison (step 4), an analysis matrix \mathbf{T}^{A} is generated. The entries of \mathbf{T}^{A} are named t_{mn} . In this mathematical description, t_{ij} are the entries of $\mathbf{T}_1^{\text{int/ext}}$ (the technology matrix, internal or external, of product one) and t_{kl} are the entries of $\mathbf{T}_2^{\text{int/ext}}$ (the technology matrix, internal or external, of product two).

If two entries in the matrices of the compared products \mathbf{T}_1 and \mathbf{T}_2 are the same and their value is equal to one, which means that the same assembly technology is used, the entry in \mathbf{T}^{A} is one. If the two entries are equal to zero, i.e. the technology is not used, then the entry in \mathbf{T}^{A} is also zero. And if the two entries differ, then t_{mn} is -1. Equation (IV.9) below details the entries t_{mn} and shows the analysis matrix \mathbf{T}^{A} .

$$\mathbf{T}^{\text{A,int/ext}} = \begin{pmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots & t_{mn} \end{pmatrix} \text{ with } t_{mn} = \begin{cases} 1 & \text{if } t_{ij} = t_{kl} = 1 \\ 0 & \text{if } t_{ij} = t_{kl} = 0 \\ -1 & \text{else} \end{cases} \quad \forall i, j, k, l, m, n \in \mathbb{N}^6 \quad (\text{IV.9})$$

Based on this, the similarity indices S_3 and S_4 are calculated. The standard calculation method consists of applying Jaccard's similarity coefficient [Jaccard 1901, p.72]. Its general calculation method is the size of the intersection divided by the size of the union in a sample set of two populations A and B as shown in equation (IV.10).

$$J(A, B) = \frac{|A \cap B|}{|A \cup B|} \quad (IV.10)$$

Applied to the similarity calculation, the indices S_3 and S_4 are calculated with the same formula. For S_3 , the matrix $\mathbf{T}^{A, \text{int}}$ must be used. And for S_4 , the matrix $\mathbf{T}^{A, \text{ext}}$ must be used.

$$S_{3,4} = \frac{\sum_1^n t_{mn} \text{ for } t_{mn} = 1}{(\sum_1^n t_{mn} \text{ for } t_{mn} = 1) + (\sum_1^n |t_{mn}| \text{ for } t_{mn} = -1)} \quad (IV.11)$$

The sum of all elements equal to one represent the number of common assembly technologies used. It is divided by the number of common technologies plus the number of specific technologies which is the sum of the entries having -1 . In the case, that both FSA have no internal arc or no external arc, the according similarity entries are indicated with "none", in order to distinguish them from zero similarity.

Therefore, the standard calculation of the indices S_3 and S_4 compares the assembly technologies which are common to both products with the overall number of different assembly technologies which are used in both products. The evaluation considers technologies for similarity only if exactly the same technology is used. Similarity between assembly technologies are not taken into account. This makes the similarity values for standard S_3 and S_4 calculation quite conservative.

IV.1.2.2. Extension to the standard assembly similarity calculation method

An extension of the calculations is presented in this section to introduce more refinement to the assembly technology similarity measures. The hypothesis is that similarity on the level of assembly operations induces similarity on the level on assembly technologies. To do so, an assembly technology comparison framework is presented based on the definition of assembly technology and operations.

It regroups all assembly technologies which have been defined and their belonging assembly operations regrouped in clusters according to their technology. The similarity of the assembly operations is evaluated. The values are to be filled in by an industrial expert using his knowledge about the assembly technologies and operations used in the company, using the following range of value: 0% = no similarity, 33% = low similarity, 66% = high similarity, 100% = perfect similarity. Therefore, the operation similarity matrix is a document which is specific for each company as different industries may have a different perception generating the similarity values.

Figure IV.4 illustrates the generic framework with exemplary values. The matrix is symmetric as similarity of operation 1 in regard of operation 2 is the same as similarity of operation 2 in regard of operation 1.

Operation similarity matrix		Technology 1			Technology 2		Technology 3	Technology 4		...
		Op1	Op2	Op3	Op4	Op2	Op5	Op6	Op7	...
Technology 1	Operation 1	100%	67%	33%	0%	67%	0%	0%	0%	
	Operation 2		100%	67%	0%	100%	0%	0%	67%	
	Operation 3			100%	0%	67%	33%	0%	33%	
Technology 2	Operation 4				100%	0%	0%	0%	0%	
	Operation 2					100%	0%	0%	67%	...
Technology 3	Operation 5						100%	0%	67%	
Technology 4	Operation 6							100%	0%	
	Operation 7								100%	
...										

Figure IV.4. Assembly technology similarity – generic framework with exemplary values

Overall similarity is calculated by the mean of the similarity values for all assembly operations in a cluster which are located on the intersection of two different assembly technologies. It has been found that the aggregation by the mean-operator is the most adapted way to calculate the technology similarity (in comparison to the operators “median”, “min” and “max”).

The technology similarity for the same assembly technology is set to one automatically – it concerns the yellow entries in Figure IV.4 – and similarity entries for no similarity are set to -1 automatically – it concerns the blue entry in Figure IV.4. These values are needed in the formula for the calculation of S_3 and S_4 (IV.13). For the exemplary framework above, the values in Table IV.3 are obtained. The entries of this table are called μ .

Table IV.3. Example of technology similarity values μ

μ	Technology 1	Technology 2	Technology 3	Technology 4
Technology 1	1	0.39	0.11	0.1667
Technology 2		1	-1	0.1675
Technology 3			1	0.335
Technology 4				1

These values are integrated in the assembly technology evaluation. For this purpose, the definition of the technology analysis matrices T^A (see equation IV.9)) has to be adapted:

$$T^{A,int/ext} = \begin{pmatrix} t_{11} & \dots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{m1} & \dots & t_{mn} \end{pmatrix} \text{ with } t_{mn} = \begin{cases} 1 & \text{if } t_{ij} = t_{kl} = 1 \\ 0 & \text{if } t_{ij} = t_{kl} = 0 \\ \mu & \text{else} \end{cases} \quad \forall i, j, k, l, m, n \in \mathbb{N}^6 \quad (IV.12)$$

The values for perfect similarity (1), no similarity (-1) and no technology (0) are maintained. The range of possible values is enlarged by adding the technology similarity values. These are obtained by comparing the assembly technologies which

are used in the same FSA in both products: by choosing the maximum value which is admissible. For example, for the same FSA, Technology 1 is used in product 1 and the technologies 2, 3 and 4 are used in product 2. Possible similarity values are 0.39, 0.11 and 0.1667 (first line in Table IV.3). The maximum value out of these three is 0.39. This value is therefore inserted in the matrix T^A . A process to choose the appropriate μ is introduced in Figure IV.5.

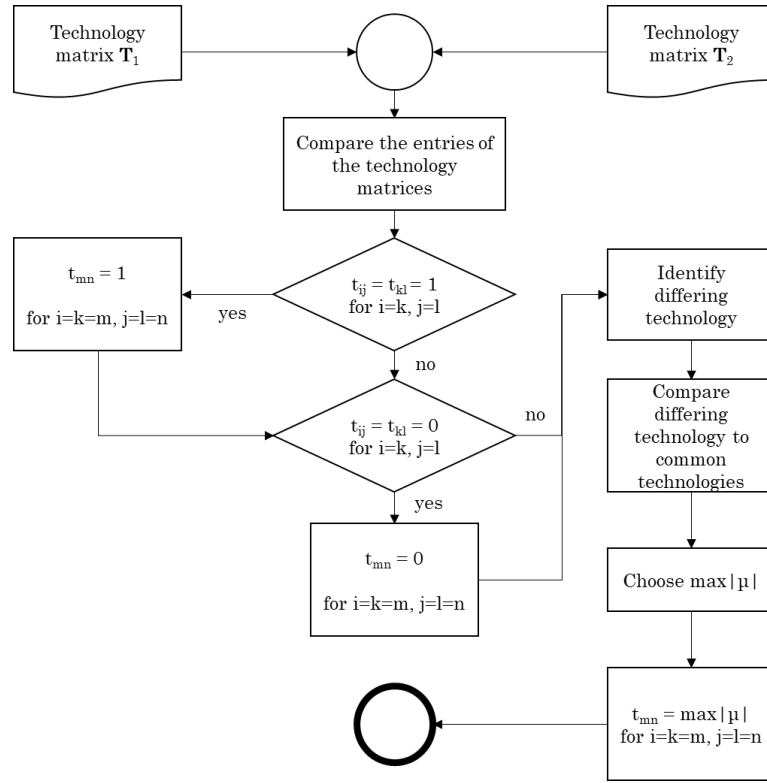


Figure IV.5. Technology similarity value selection process

Following the modification of the similarity value calculation, the similarity evaluation is adapted accordingly:

$$S_{3,4} = \frac{\sum_1^n t_{mn} \text{ for } t_{mn} > 0}{(\sum_1^n t_{mn} \text{ for } t_{mn} = 1) + (\sum_1^n |t_{mn}| \text{ for } t_{mn} = -1) + (n \text{ for } 0 < t_{mn} < 1)} \quad (IV.13)$$

The sum in the numerator is taking into account not only values equal to one but all values greater than zero, therefore also the newly defined similarity values. In the denominator, the last term is added which counts the number of entries which contain the new similarity values.

To sum it up, the extension to the standard similarity calculation offers a more finely-shaded view of assembly technology similarity. It considers the impact of assembly operation similarity by technology clusters. The proposed technology evaluation is human based, an industrial expert is needed, by using a scale from zero to one divided into four categories. However, the table can be filled with help of more sophisticated methods as the multi-criteria analysis (for example a cost-utility analysis, see also [Dubbel and Beitz 1997, pp. F7-F10]) or an analytic hierarchy process as presented for example by [Saaty and Vargas 2012].

Example IV.2: Assembly technology similarity analysis of different pen types

For the analysis of the assembly technologies used in ball pen and feather pen, their enriched DFC with FSA and assembly technology information have to be compared. Both DFCs are illustrated in Figure IV.6. As a reminder: BA= bolted assembly; C= Clipping; F= filling; PC= placing-charging; PP= press-fitting and plaiting; PS= plastic deformation and seaming.

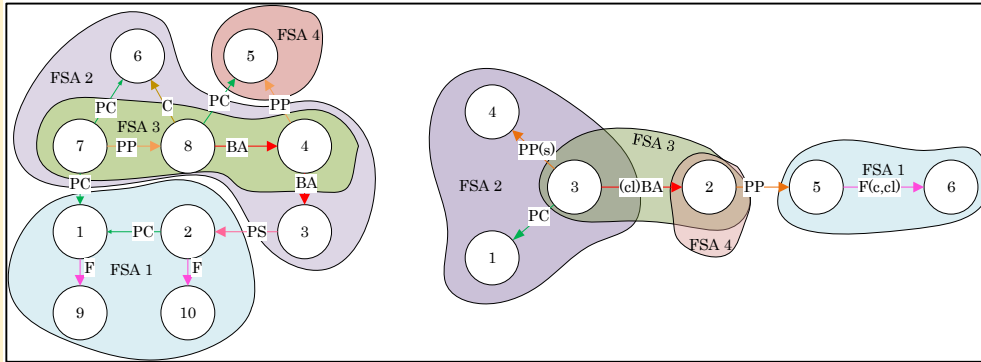


Figure IV.6. DFC with FSA and assembly technologies for feather pen (left) and ball pen (right)

The four assembly technology matrices (internal and external) for both pens are indicated in the following. Line and column labels have been added to identify easily FSA and technology.

$$T_{bp}^{int} = \begin{pmatrix} & BA & C & F & PC & PP & PS \\ FSA1 & 0 & 0 & 1 & 0 & 0 & 0 \\ FSA2 & 0 & 0 & 0 & 1 & 1 & 0 \\ FSA3 & 1 & 0 & 0 & 0 & 0 & 0 \\ FSA4 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad T_{bp}^{ext} = \begin{pmatrix} & BA & C & F & PC & PP & PS \\ FSA1 & 0 & 0 & 0 & 0 & 1 & 0 \\ FSA2 & 0 & 0 & 0 & 0 & 0 & 0 \\ FSA3 & 0 & 0 & 0 & 0 & 0 & 0 \\ FSA4 & 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$T_{fp}^{int} = \begin{pmatrix} & BA & C & F & PC & PP & PS \\ FSA1 & 0 & 0 & 1 & 1 & 0 & 0 \\ FSA2 & 1 & 1 & 0 & 1 & 1 & 0 \\ FSA3 & 1 & 0 & 0 & 0 & 1 & 0 \\ FSA4 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad T_{fp}^{ext} = \begin{pmatrix} & BA & C & F & PC & PP & PS \\ FSA1 & 0 & 0 & 0 & 1 & 0 & 1 \\ FSA2 & 0 & 0 & 0 & 0 & 0 & 0 \\ FSA3 & 0 & 0 & 0 & 0 & 0 & 0 \\ FSA4 & 0 & 0 & 0 & 1 & 1 & 0 \end{pmatrix}$$

Example IV.2 (continued)

For standard similarity evaluation, the matrices $T^{A,int}$ and $T^{A,ext}$ are generated:

$$T^{A,int} = \begin{pmatrix} 0 & 0 & 1 & -1 & 0 & 0 \\ -1 & -1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad T^{A,ext} = \begin{pmatrix} 0 & 0 & 0 & -1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & -1 & -1 & 0 \end{pmatrix}$$

The following assembly technology similarity values are obtained:

Table IV.4. Assembly similarity calculation for pen types

[%]	FSA 1	FSA 2	FSA 3	FSA 4	FSA 5
S3	50	50	50	none	0
S4	0	none	none	0	0

IV.1.2.3. Interpretation of assembly similarity (S_3 and S_4)

The similarity indices S_3 and S_4 evaluate two different aspects concerning the product assembly:

- S_3 evaluates the similarity of assembly technologies used to assemble the same FSA in two products. That means the similarity value indicates if the same technologies are used to realise the mechanical links which are situated in the FSA. High values for S_3 indicate therefore that the FSA of both products are supposed to be assembled in the same module of the production system.
- S_4 evaluates the similarity of assembly technologies used to assemble the same FSA of two products with the other FSA. That means the similarity value indicates if the same technologies are used to realise the mechanical links which are connecting a FSA to the other ones. High values of S_4 indicate therefore that the FSA of both products is supposed to be assembled with the rest of the products in the same module of the production system.

Concerning the similarity values, 100% indicates that no technology change is necessary. The concerned modules should only contain the needed flexibility to cope with differing assembly parameter values and differing geometric datum positions.

Values under 100% indicate the need for reconfiguration, i.e. the change of assembly technologies in the same module. If the similarity value is too low, reconfiguration efforts are too high and the separation of the production flow should be considered. The according threshold value has to be defined specifically for each industrial application.

In one industrial application it has been defined that, if $S_3 > 50\%$, a common installation for functional subassembly (FSA) can be recommended and, if $S_4 > 50\%$, a common installation for the product assembly, i.e. the connection of a functional subassembly with the other parts of the product, can be recommended. The values of 50% have been fixed during a first analysis with the industrial partner.

IV.2. Similarity indicator applications

In the precedent sections, generic interpretations of the similarity indicators S_1 to S_4 have been presented. In the following, four different detailed application cases are presented, in whom the indicators are used for product design, product family generation and improvement, and production system deductions. Figure IV.7 illustrates the applications and their location in the document.

Product family generation and product design analysis can be linked to product family design improvement as the latter can be seen as an additional application based on the former ones. Three analysis strategies can be deployed for the interpretation of the similarity analysis results: statistical analysis can be applied for product family generation and portfolio design analysis. Unsupervised learning can be applied to product family generation. And supervised learning can be employed for portfolio analysis and production system deductions. Finally, an iterative method is introduced for the product design similarity improvement.

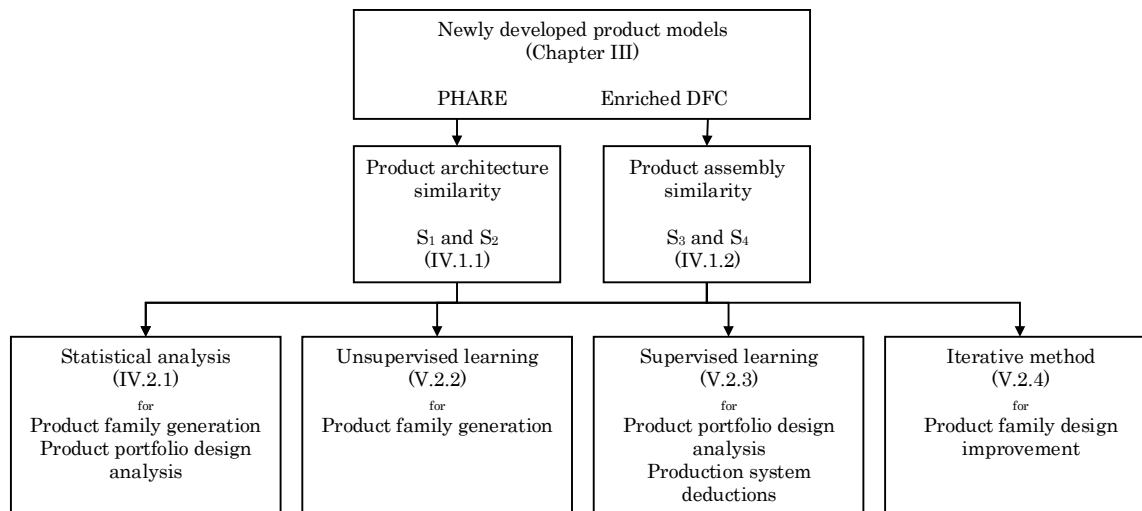


Figure IV.7. Similarity indices and their applications

IV.2.1. Statistical analysis of similarity analysis results

Statistical analysis means that statistical operations are done on the entire population which has been generated by calculating the indices S_1 to S_4 for all functional subassemblies of all the products which have to be examined. These operations can be the aggregation of the similarity indices into only one criterion to have a glance on the global product similarity to compare and group them (product family generation). Or to have a more precise view by considering each similarity indices (from S_1 to S_4) on each functional module (portfolio design analysis). Possible applications are product family generation or product portfolio design analysis.

IV.2.1.1. Product family generation with statistical analysis

Product family generation is supported by the indices S_1 and S_2 . The aim is to regroup the products which have high values for S_1 and S_2 . The Figure IV.8 illustrates the mapping of ten different products obtained during an industrial case study. The grey zone highlights the intersection of the best ten binary comparisons for S_1 and S_2 .

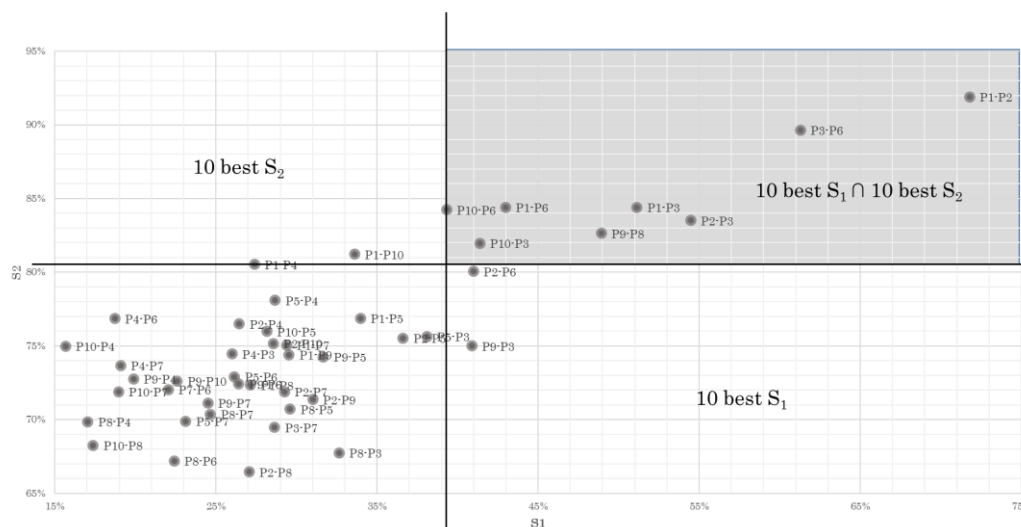


Figure IV.8. Product similarity mapping with S_1 and S_2

The values of the individual S_1 and S_2 scores by functional subassembly have been aggregated into one global similarity score on the product level by the mean-operator. This mapping illustrates in an easy way all binary product comparisons of the examined product portfolio. It helps to identify easily the product combinations having the best similarity values. It furnishes as well a decision making support when the question is to find the most appropriate match for a given product. For example, when the question is to regroup product P_1 with another product it can easily be seen that the combination P_1 - P_2 is the best solution in terms of product architecture similarity.

IV.2.1.2. Product portfolio design analysis with statistical methods

The architectural similarity indices S_1 and S_2 can be used for the identification of varying and unvarying product architecture elements (by functional subassembly) throughout an entire product portfolio. For the analysis, the similarity values for all of the products (of all binary comparisons) have to be calculated. In a second step, the values can be analysed as illustrated in Table IV.5. The combination of maximum values, mean and 10% quantile gives an overview of the overall product design similarity.

In the table, 11 exemplary FSA are listed. They and their according values represent an excerpt of an industrial application comparing a panel of 10 products. It can be seen that the FSA highlighted in grey have full maximum values at least in one comparison. In addition, mean and median are high and the 10% quantile is near 100%. These are indicators that the considered FSA are similarly realised (indicator for standard solutions). Whereas a large number of FSA is not similar throughout the examined product portfolio.

Table IV.5. Example for product design analysis with S_1

Functional subassembly	Max S_1	# comparisons having max	mean	median	10% quantile
1	100%	3	73%	75%	95%
2	100%	3	73%	75%	95%
3	78%	2	41%	38%	59%
4	65%	1	27%	27%	57%
5	82%	1	37%	34%	72%
6	100%	1	15%	11%	40%
7	67%	1	13%	11%	34%
8	88%	1	38%	36%	61%
9	100%	1	37%	34%	58%
10	100%	3	33%	17%	90%
11	100%	16	63%	75%	100%

IV.2.2. Unsupervised learning approaches

Unsupervised learning is an approach that searches for patterns in a data set without or at least with a minimum of human guidance. It is suited for clustering applications when the number of clusters and the content of the clusters is not known. Therefore, it fits perfectly for an application on product family generation.

IV.2.2.1. Product family generation with unsupervised learning approaches

The product family generation method with statistical analysis is limited to binary comparisons and decisions. To enable multi-product clustering based on S_1 and S_2 , a software tool has been developed in the context of the research cluster. This section shows a clustering approach developed by [Brunstein 2019] in a Bachelor thesis linked with the research project. It is based on the presented approaches for product modelling and uses the product model to calculate S_1 and S_2 . The implementation enables clustering with four different methods: k-medoids, hierarchical clustering, a genetic algorithm based on clustering solutions and a genetic algorithm based on the k-medoids method. The combination of an evolutionary algorithm with the k-medoids method has been identified as the most performing of them.

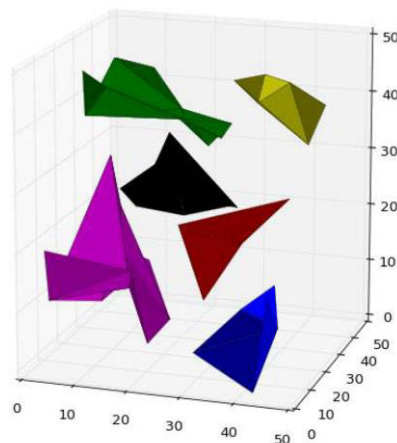


Figure IV.9. Example for product clustering based on S_1 and S_2 [Brunstein 2019]

Figure IV.9 illustrates the grouping 6 families of 50 randomly generated products with this . For this example, 22 FSA have been considered. As it results in a solution space of 22 dimensions, for the product cluster illustration in a three-dimensional picture, three FSA have been selected. Using a simple hypothesis allows to derive out of the clustering deductions for the production system: the more the design choices are close and similar, the more the manufacturing system will be easy to reconfigure or to adapt to this new product. In consequence, the products of a product cluster are supposed to be assembled on the same production line.

IV.2.3. Supervised learning approaches

The presented research can also be linked with another research challenge of the research cluster: challenge 4 - continuous improvement of complex and modular production systems using data mining approaches. In opposite to unsupervised learning approaches, the supervised ones define data domains based on predefined data-domain couples. For the application of this approach, it is therefore necessary to have

a validated data set as input. This may concern product portfolio analysis or production system deductions.

IV.2.3.1. Product portfolio design analysis with supervised learning approaches

Taking the similarity value mapping by FSA as input (Figure IV.10, upper graph), the similarity values can be divided into different categories with data mining approaches. In the graph, each FSA has its specific symbol.

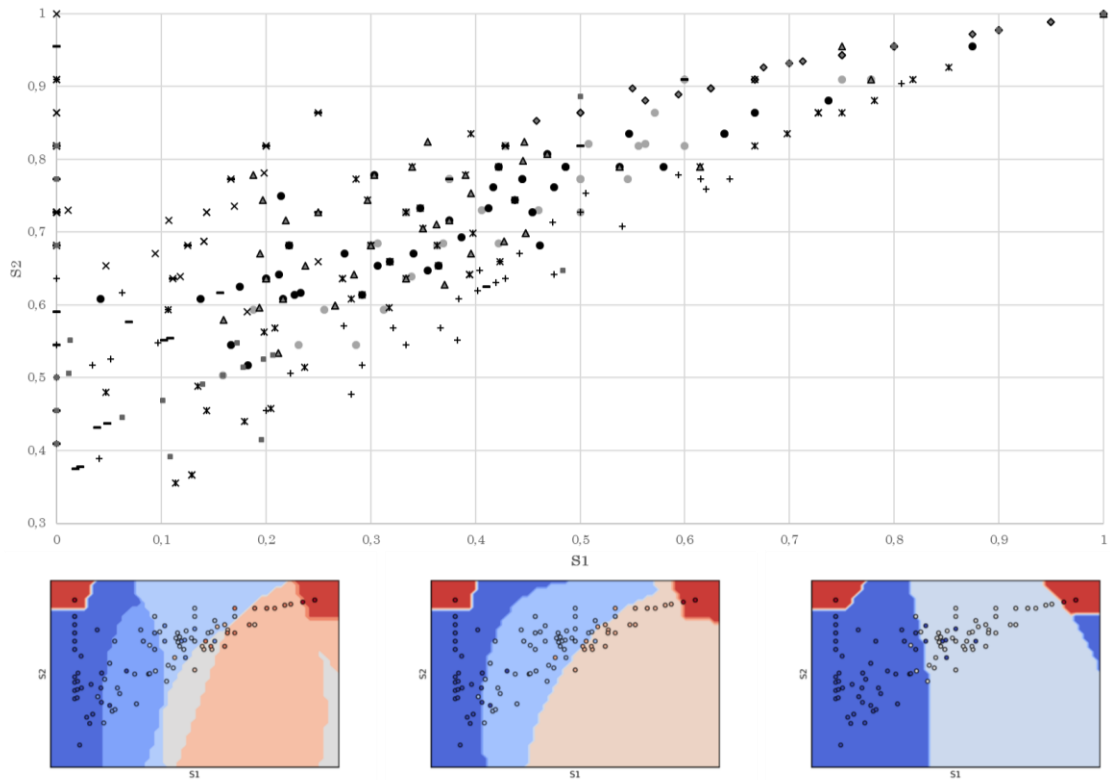


Figure IV.10. Similarity value mapping by FSA with S_1 and S_2

Support Vector Machine (SVM) has been used as classification tool [Zouhri, Homri and Dantan 2019]. The number of categories has to be determined and a population of category members has to be defined for this method. As illustrated by Figure IV.10, below, the similarity values have been classed into six categories (left), four categories (middle) and three categories (right). For example, considering three categories, it can be used to determine different domains of similarity values for the evaluation of product similarity: dark blue zones can be determined as completely dissimilar, dark red zones as completely similar and the light blue zone as similarity which needs to be improved. For the determination, as mentioned, as set of similarity values has to be validated to belong to the different domains.

The product portfolio design analysis highlights therefore unvarying FSA, varying FSA and helps to visualise the degree of architectural design similarity. On one hand, it supports the identification of standard elements in the product portfolio and elements having standardisation potential (those which are close to full similarity). On the other hand, it supports the traceability of standardisation efforts by comparing similarity values before and after standardisation.

IV.2.3.2. Production system deductions with supervised learning approaches

As mentioned, the hypothesis of the research work is that similarity on the product design and assembly level induces similarity on the level of the production system: products of a similar architecture and with similar assembly technology are likely to be assembled on the same assembly system or, the other way around, the assembly system layouts are similar for similar products (easier multi-product assembly system design).

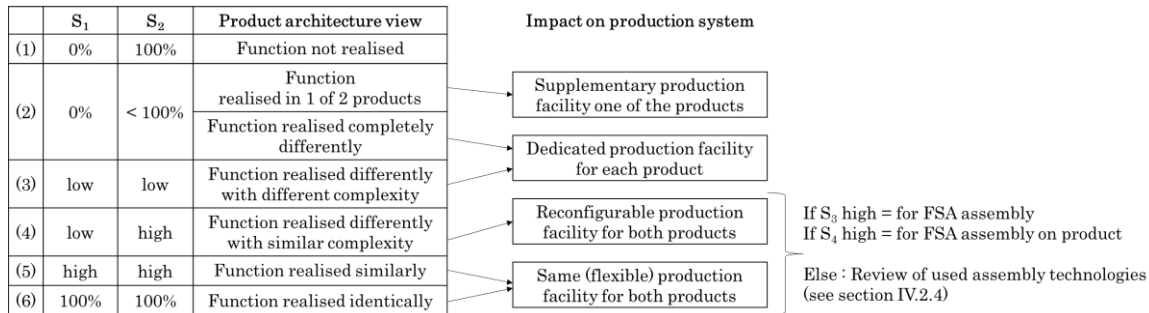


Figure IV.11. Impact of similarity analysis on production system

Therefore, the analysis of S_1 to S_4 gives information about the production system type to choose. In a first step, S_1 and S_2 are analysed. Figure IV.11 illustrates the interpretation scheme. In case (1), no deduction is taken as the FSA is not realised in both of the products. Case (2) has two possible reasons: either the FSA is realised only in one of the products or it is realised in both products but in a completely opposite way. For both reasons, the FSA should be assembled on different separated dedicated production facilities as it is either a supplementary operation or there is no common point between both products. In case (3), the similarity values are too low to allow a common assembly of both products' FSA. The different degree of complexity (S_2 low) suggests that the gap between the products is very important. Here, also the separated dedicated production facilities are to prefer. Case (4), however, has similar different complexity (S_2 high). This means that a common reconfigurable production facility is adapted and should be able to cope with differences in product design as its complexity is common. Finally, the cases (5) and (6) indicate high design and complexity similarity which means that the FSA of both products can be assembled on the same common production entity. If necessary, a flexibility margin has to be included but reconfigurability is not needed.

Support Vector Machine or similar supervised learning approaches can be used to define the boundaries of the three intermediate categories (3) – (5). To do so, the values of products which can be assigned with certainty to one of them have to be taken as verified input. In this case, the coloured categories in Figure IV.10 will represent one of the categories defined in Figure IV.11.

After the analysis of S_1 and S_2 , for the FSA which are identified as admissible for a common production, the similarity values S_3 and S_4 are studied. These determine, if the common production facility is dedicated for the assembly of the FSA or for the assembly of the FSA on the products. In addition, the reconfiguration effort needed can be estimated regarding the similarity index values (the higher the value, the lower is the reconfiguration effort as more assembly technologies are in common). If the similarity values of S_3 and S_4 are low, an improvement of product similarity (see section IV.2.4) should be considered.

IV.2.4. Product family similarity improvement

The last application of the similarity indices is their use for product family similarity improvement. The overall similarity analysis as presented could for example highlight the need of a similarity improvement. For this purpose, an iterative process is presented in this section. A description of the process with an application is available in [Stief et al. 2020]. This product improvement process based on similarity evaluation is illustrated in Figure IV.12. The iterative method can be positioned in a reverse engineering approach. It may be referred to the approach of Function-Behaviour-Structure (FBS) as introduced by [Gero 1990] and [Gero and Kannengiesser 2004]. Regarding the FBS, the iterative product family improvement method would be located in the link B to S. The structure is represented by the analysed product and the behaviour is its technical function.

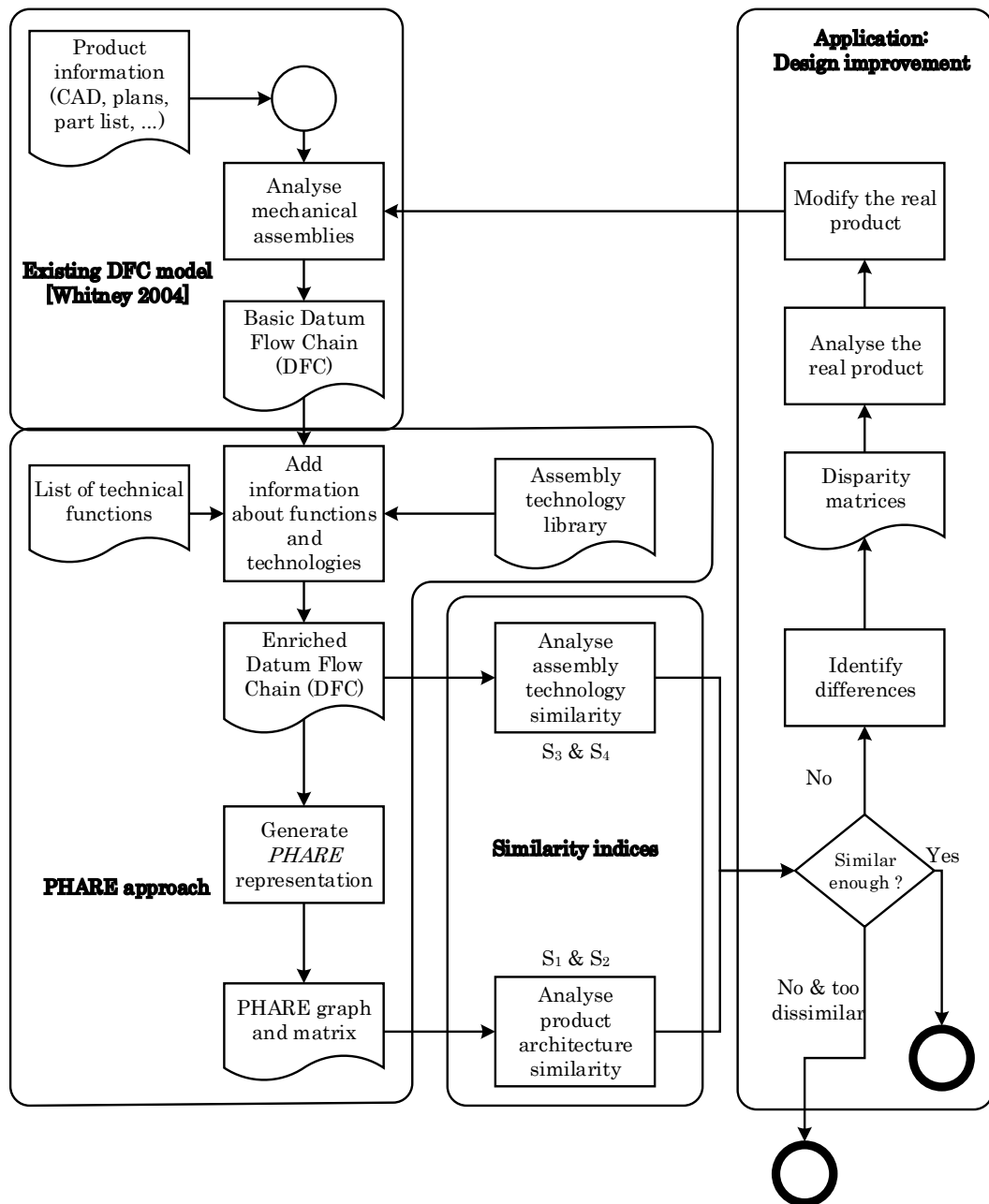


Figure IV.12. Detailed view on the iterative process

As illustrated in Figure IV.12, the product improvement approach is linked to the extended DFC model, the PHARE product model and its similarity indices. The iterations switch between the models, their use in form of the similarity indices and the real product – real in the sense that it concerns the manufacturing of the final product and not the modelling part. The iterative method is applicable on two products at the same time. It relies on the analysis of disparities in the PHARE representation and their reduction (ideally: elimination). Its objective is to increase significantly the similarity of two products in terms of product architecture and assembly technology. The reasoning focuses first on the product architecture analysis and improvement. Then the assembly technology similarity is assessed and improved during the assembly technology improvement loop.

The product architecture improvement is based on the PHARE matrices. To identify the functional subassemblies which cause low similarity in the PHARE, a so-called *disparity matrix* is generated for each of the both products. These disparity matrices contain all relations which *are not the same (technically too dissimilar)* in the PHARE matrices. Thus, all non-empty cells of this comparison matrix refer to a difference in the functional allocations. These non-null entries can have the same values as in the PHARE matrices.

Referring to the two different PHARE matrices which have been mentioned in the precedent section: in this mathematical description, p_{ij} are the entries of \mathbf{P}_1 (the PHARE matrix of product one) and p_{kl} are the entries of \mathbf{P}_2 (the PHARE matrix of product two). The disparity matrices \mathbf{D}_1 , with the entries d_{ij} for product one, and \mathbf{D}_2 with the entries d_{kl} for product two, are calculated as indicated in equation (IV.12) and (IV.13).

$$\mathbf{D}_1 = \begin{pmatrix} d_{11} & \cdots & d_{1j} \\ \vdots & \ddots & \vdots \\ d_{i1} & \cdots & d_{ij} \end{pmatrix} \text{ with } d_{ij} = \begin{cases} p_{ij} & \text{if } p_{ij} \neq p_{kl} \quad \forall i = k, j = l \quad \forall i, j, k, l \in \mathbb{N}^4 \\ 0 & \text{else} \end{cases} \quad (\text{IV.14})$$

$$\mathbf{D}_2 = \begin{pmatrix} d_{11} & \cdots & d_{1l} \\ \vdots & \ddots & \vdots \\ d_{k1} & \cdots & d_{kl} \end{pmatrix} \text{ with } d_{kl} = \begin{cases} p_{kl} & \text{if } p_{kl} \neq p_{ij} \quad \forall i = k, j = l \quad \forall i, j, k, l \in \mathbb{N}^4 \\ 0 & \text{else} \end{cases} \quad (\text{IV.15})$$

An example for two disparity matrices is given in Figure IV.13. The entries which differ in the PHARE matrices are highlighted in red. Based on the disparity identification, the reasoning is to reduce the entries in the disparity matrix as much as possible which means that the differences in the PHARE matrices are reduced. The aim is to have the same entries in the PHARE matrices and, therefore, in some ideal case disparity matrices which have only zero entries. One disparity matrix per product is needed to display all the differences. For example, the first two entries in line four of \mathbf{P}_2 are different to the corresponding entries in \mathbf{P}_1 . However, this difference is only displayed in \mathbf{D}_1 . The processing of disparate entries follows the hierarchy of PHARE relations as presented in Chapter III.

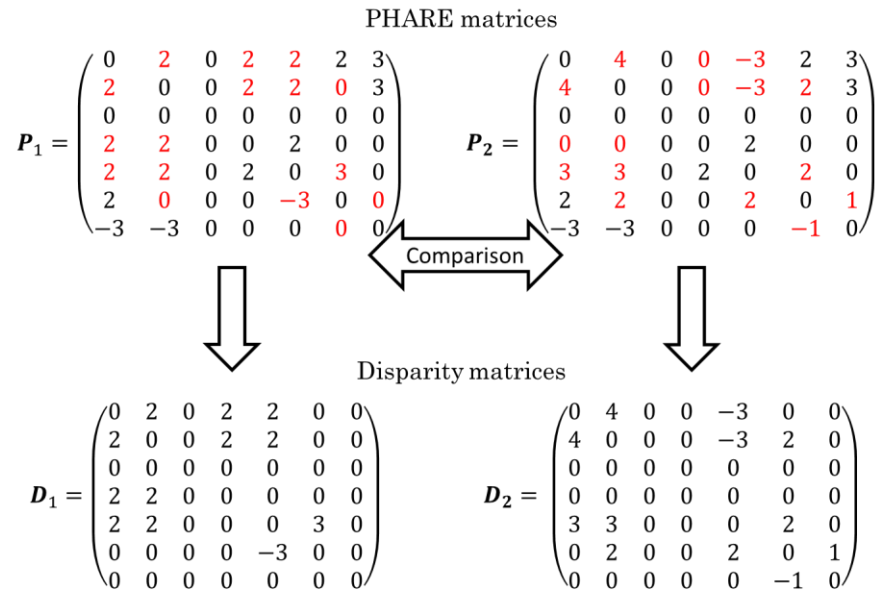


Figure IV.13. Example of two disparity matrices

At first, the entries of the type *identities* have to be treated. Afterwards, due to the transitivity rule, the differences concerning relations of the type *inclusion* have the most impact on the PHARE and thus on the product similarity indices S_1 and S_2 . In consequence, the examination order is from strong primary relations, over weak primary relations to secondary relations. The entire iterative process is illustrated in Figure IV.14. At first, product design is evaluated in regard of the similarity indices S_1 and S_2 . Then, in a second step, assembly technology is examined with S_3 and S_4 . The order is necessary as changes in design to increase S_1 and S_2 values have an impact on the assembly technology evaluation. It can be done once the product design is fixed.

Based on the difference analysis, the improvement loop starts with the identification of identities. Once identified in the disparity matrices, their location in the product architecture is known through the FSA which are implied. In a next step, the real product is examined concerning the critical FSA and a solution is proposed to remove the differences and to increase similarity. It is the task of the product designer to assure that the proposed solution removes the difference and satisfies at the same the technical requirements on the product.

When a solution is applied, the PHARE matrix and the disparity matrix are updated, and a new iteration starts analogous to the described one. The iterations of the product improvement loop finish when there are only “contact” relations left which are considered as not important to modify.

The presented approach is a support for product designers, helping them to identify parts of the product which are differing compared to another one. The comparison on the FSA level helps to identify the location of the differences in the real product. Due to the binary comparison two possibilities for redesign exists: either the designer can change the design of both products, which could be the case when adapting two products under development to each other. Or the designer adapts one of the two existing products, for example in the case of the adaptation of a product under development to an existing one. Also, if the circumstances allow it, the aim may be to reuse an already existing production system at a maximum.

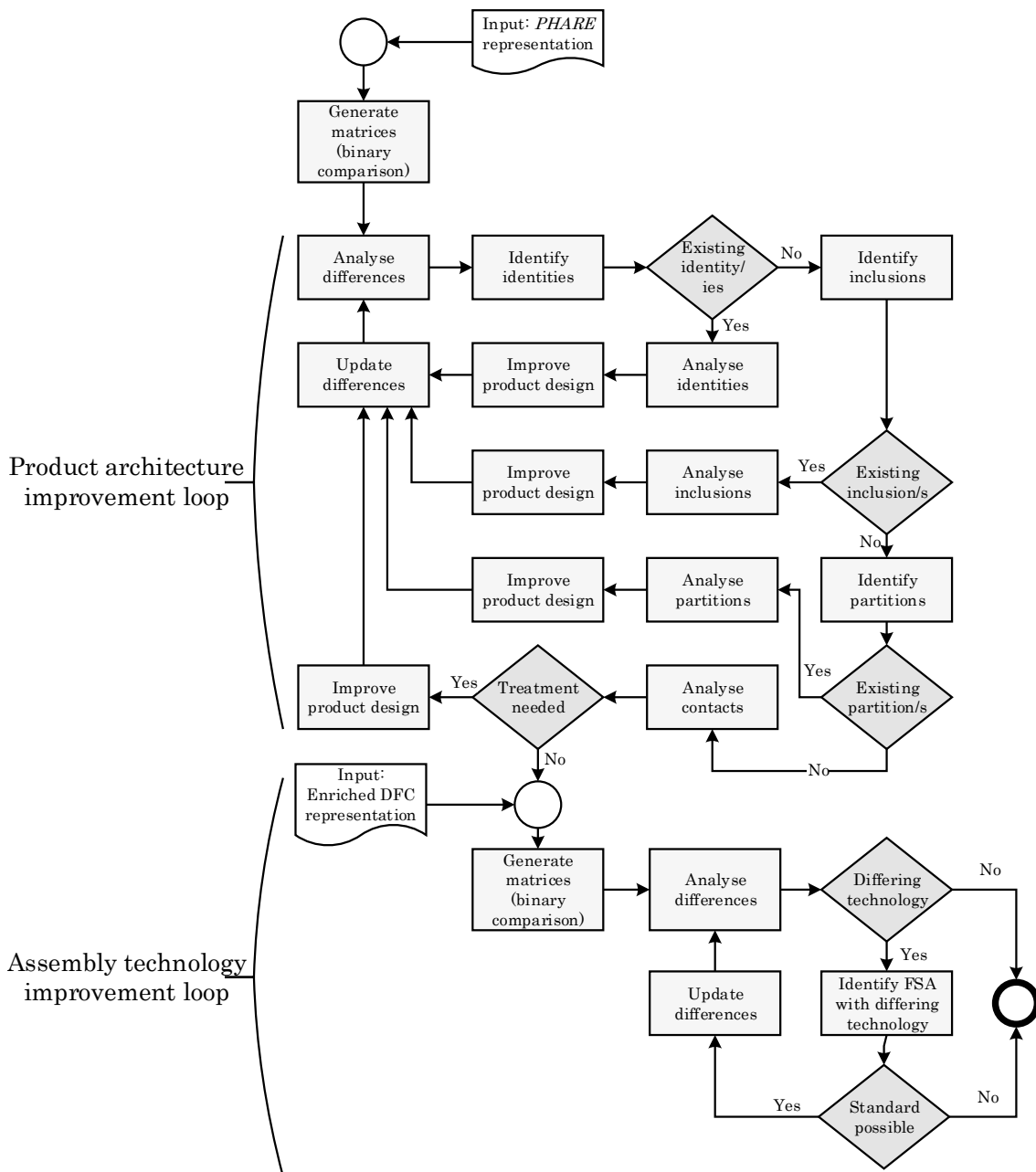


Figure IV.14. Iterative process for product similarity improvement

The approach does not prescribe any technical solution neither aims to reach a globally optimal solution. It aims to reach a local optimum in the comparison of two products and supports the decision-making process leading to this local improvement. The final decisions which modifications have to be applied are up to the designer. When the product architecture improvement loop is finished, the assembly technology improvement loop starts. To do so, the updated product structure (enriched DFC) is used to calculate the similarity indices S_3 and S_4 . Based on this, differences in used assembly technologies are identified. With help of the FSA, the differences can be located in the real product. It is task of the product designer to identify if a common assembly technology solution can be proposed for both products and which satisfies their technical requirements. The change of technologies can also induce changes in product design. Equal to the product architecture improvement, the approach gives no restriction of the detailed solution but guides the designer during the identification of

differences. It is up to the product designer to ensure that the proposed assembly technology solution satisfies the product requirements.

Example IV.3: Product design similarity improvement for different pen types

Based on the PHARE matrices of ball pen and feather pen (previously illustrated), the disparity matrices for both products can be generated. As there is no common relation in both products, the disparity matrices are equal to the PHARE matrices. The iteration is indicated by the exponent of the disparity matrix. For the example, the assumption is taken, that the ball pen design can be changed and the design of the feather pen is fixed.

$$D_b^0 = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 3 & 0 \\ -1 & 0 & -3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}; D_f^0 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ -1 & -3 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

There are no identity relations. The improvement starts with the modification of the relation between FSA 3 (enable ergonomic handling) and 4 (ensure contact with paper) of the ball pen (inclusion in ball pen PHARE and contact in the feather pen PHARE). The aim is to transform the inclusion into a contact.

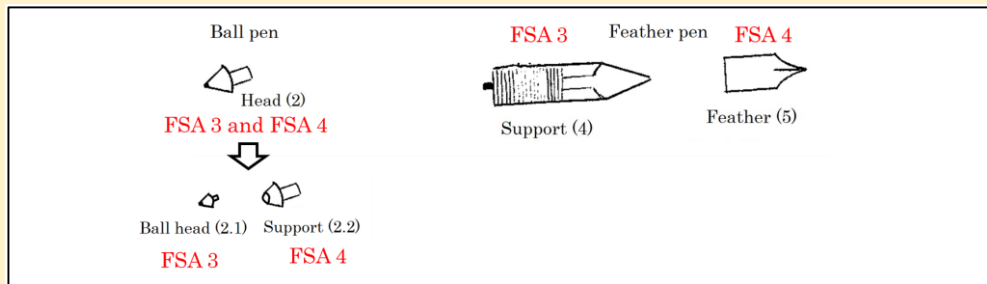


Figure IV.15. Product change for similarity improvement

The solution is to separate the technical functions of the ball pen by separating head and support as illustrated in Figure IV.15. The updated enriched DFC and PHARE are illustrated in Figure IV.16.

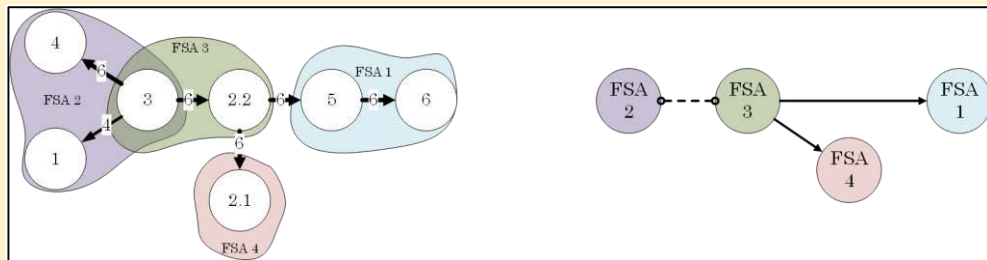


Figure IV.16. Updated PHARE and enriched DFC of the ball pen

Out of the modified product model, the new PHARE matrix for the ball pen and the new disparity matrices are generated. It can be seen that with the treatment of the inclusion between FSA 3 and FSA 4 the contact relation (marked in red) has shifted and is now in accordance between ball pen and feather pen.

$$P_b^1 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ -1 & 2 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}; P_f = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ -1 & -3 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$D_b^1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}; D_f^1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 3 & 0 & 0 \\ 0 & -3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Regarding at the two disparity matrices, only one relation is left to treat to obtain optimum similarity. The *partition* relation between FSA 2 (prevent ink form drying) and FSA 3 has to be transformed into an *inclusion* relation. This can be achieved by designing the newly introduced support (component 2.2 in Figure IV.15) in a way that its airtightness participates to the realisation of FSA 2. In consequence, component 2.2 must be integrated to FSA 2, as illustrated in Figure IV.17.

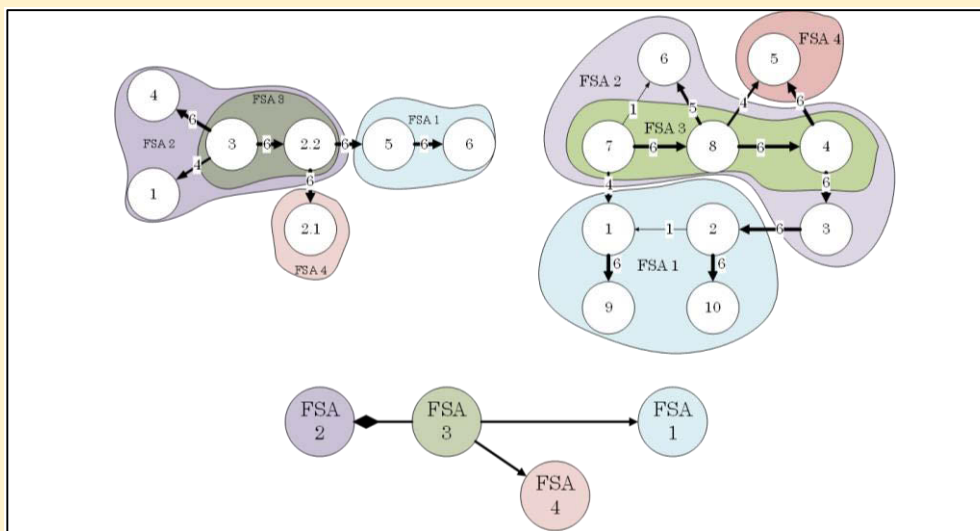


Figure IV.17. Enriched DFC of ball pen (left) and feather pen (right) and their common PHARE

Similarity values for S₁ and S₂ have been increased to 100% for all four realised FSA. The product design similarity improvement loop is now closed.

Example IV.3.2: Product assembly technology improvement for different pen types

The assembly technologies used in the initial ball pen and feather pen design have already been illustrated in Figure IV.6. They are the starting point for this assembly technology improvement loop. Table IV.4, at the same place, gives the initial similarity values. It is evident, that no perfect similarity exists in the initial design.

The improvement process starts with FSA 1 (S₃ = 0,5; S₄ = 0). The differences in S₃ are due to the fact that the feather pen has two cartridges, one placing the other. Differences in S₄ are due to the two cartridges as one is loose and in contact with the pen body. In addition, the technology for connecting the cartridge to the support is different. Two actions have to be undertaken: first, replace two cartridges by one big one. And second, replace the plastic deformation-seaming technology in the feather pen with the press fitting-plaiting operation of the ball pen.

FSA 2 differs only in S₃ as there is no value for S₄ (*none*). To achieve full similarity, the bolted assembly and clipping technology of the feather pen has to be replaced by press fitting-plaiting.

In FSA 3, S₃ is differing by the bolted assembly of the ball pen (the bolted assembly in the feather pen has been changed in the step before). Therefore, it has to be changed to press fitting-plaiting.

For FSA 4, S₄ only has to be treated. The bolted assembly of the ball pen has already been changed to press fitting-plaiting. Only the placing-charging technology in the feather pen has to be changed. Either it is changed to press fitting-plaiting as well or the product design is changed to eliminate the mechanical link.

Finally, FSA 5 is not realised and therefore not considered. The enriched DFC models obtained at the end are illustrated in Figure IV.18.

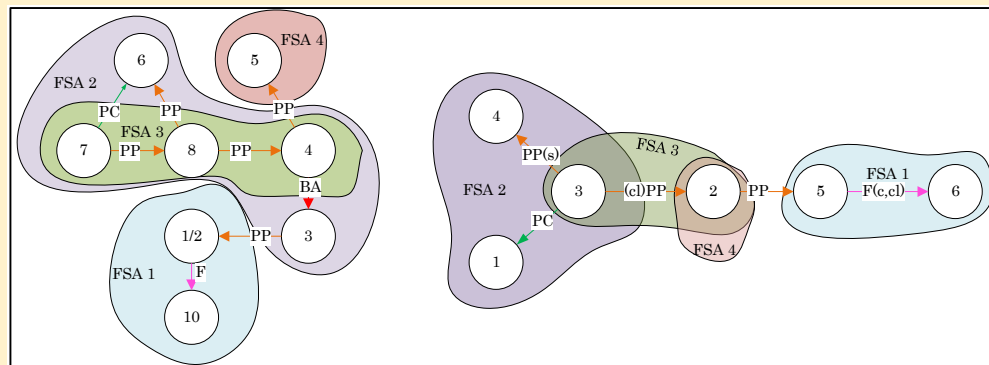


Figure IV.18. Enriched DFC of ball and feather pen after technology similarity improvement

A step by step illustration is joined in Appendix D.

The assembly technology improvement loop finishes, when all differences in assembly technology are analysed and no further improvement can be proposed. With this loop, the new proposed product design improvement process as illustrated in Figure IV.14 arrives at its end. Both loops, the one for product design similarity improvement and the one for product assembly technology improvement can be done independently if needed. For this, the loops can be separated on their transition (in Figure IV.14 before the starting point of the assembly technology improvement loop).

As mentioned, the approach does not prescribe a technical solution. It supports the identification of differences in product design and assembly technology choices. The final decision which changes are reasonable and efficient are up to the designer. A method for the evaluation of possible solutions is not furnished by the iterative process. For an evaluation of different possible solutions in terms of cost or assembly efforts, classical methods used in Design for Assembly (DFA) methodologies can be coupled to the iterative process. They are to be applied during the “improve product design” stages in the iterative process. An overview of some common DFA approaches is proposed by [Boothroyd and Altung 1992] and [Leaney and Wittenberg 1992].

IV.3. Conclusions of the chapter

For the design of manufacturing and assembly systems, it is important to know which products will be sent on production, which production paradigm to choose and where in the assembly system the reconfiguration has its optimum application. To answer the question of product mix, several commonality indices have been proposed in the past, ranging from simple part-by-part comparisons to evolved indices considering additional aspects as for example material. But all these indices fail to answer the question which production paradigm to choose, where to integrate reconfigurability and assembly technology is rarely considered. Addressing this research gap, a new similarity analysis approach is proposed in this chapter, based on the parallel analysis of four similarity indices:

- S_1 and S_2 for a general view on the similarity of the product structure (functional and physical) which guide towards the production paradigm to choose and which give an idea about the complexity of the products in terms of technical functions.
- S_3 and S_4 which detail the similarity on an assembly level. They give an information on the difficulty of reconfiguration (different or identic technologies) on the level of the assembly system installations.

An introduction of the similarity indices can be found in [Stief et al. 2019]. The applicability and effectiveness of the indices have been verified in cooperation with the industrial partner, several case studies have been carried out. They underline that a comparison of different products (differing in number and characteristics of their components) is possible with these new indices. The confrontation of these first case study results with the experience of the industrial partner has revealed that the propositions are in concordance with what is considered possible and reasonable by the industrial partner. In consequence, the indices fulfil the requirements which have been defined in the beginning of this chapter.

Concerning the indices themselves, it has been revealed that the understanding of the meanings of S_1 and, especially, S_2 is not easy to apprehend for novices. This implies, when deploying these indices in other companies or to not trained operators, complementary efforts are necessary to accompany the deployment.

Concerning the applications, further work on the industrial use cases is needed. First, the deductions for the production system choices have been validated theoretically by the industrial partner but a production system based on these deductions has not been implemented and put into service yet. And second, the product improvement loop is for instance limited to technical solution analysis, i.e. it provides a solution space of possible design changes but no evaluation or decision making support. Neither the financial or practical impact of the solutions is evaluated. The coupling with DFA methods is a promising perspective to add the dimension of cost and effort evaluation. These can be for example the integration of DFA methods as presented by [Boothroyd and Alting 1992] and [Leaney and Wittenberg 1992]. Concerning a decision making support, multi-criteria evaluation processes as the AHP [Saaty and Vargas 2012] can be employed. It should be examined if they can be coupled efficiently to the presented product similarity improvement process.

Also the compatibility of the PHARE modelling and improvement in the context of classical development methods can be examined. During the industrial case study, it

has been confirmed that the PHARE approach may be applied during early design stages in order to give a feedback from production to the design department. During these stages, changes can more easily be made and are less costly as after the detailed design stage. It is to verify, if this specific applicability in the context of the partner company can be generalised. This means, if the information generated during early design stages is in general sufficient for the PHARE modelling. For this, the coupling of widely taught and used systematic design approaches (for example [Pahl, Beitz and Wallace 2001]) with the PHARE modelling and improvement iterations during the stages of concept design and embodiment design might be examined.

As already been mentioned in this chapter, the design improvement process can be expressed in the FBS model, to give an example of its compatibility with other approaches, although the FBS is not in the centre of this research work. The same model has been used by [Baqai 2010] for the co-design of manufacturing processes and systems. When it comes to the modelling of a generic methodology for system design englobing the approaches presented in this research work, the combination of both approaches in an overall FBS structure may be realised to formalise a FBS model for the co-design of the triad of product, process and system in the context of assembly.

Finally, concerning the definition of uncertain domains which concerns particularly the intermediate values of S_1 and S_2 , future work should consist of the determination of their boundaries. The frontiers can be determined by establishing fuzzy rules or using classification tools as for example support vector machine (SVM) which has been illustrated in the application section.

The calculations and interpretation domains for the indices have been realised by hand in a first time, which is time consuming and affected to the risk of input and calculation errors. Based on the Python software prototype which has been developed to cope with the product modelling, the calculations of S_1 to S_4 have been integrated successfully during complementary work in the context of the research project. Furthermore, the disparity matrix calculation has been added. The similarity indices and their applications, beside the product design improvement, have been applied to all of the modelled products of the industrial partner. To remind, it is a set of eleven products are differing in component number (from 20 to 70 components), the component type (mechanic, electronic, and electric), and the number of technical functions realised (from 14 to 21). For the product design improvement, two products out of eleven have been chosen, guided by a problem which the industrial partner has faced during the integration of these products to production.

To sum up, four new complementary similarity indices have been introduced in this chapter to answer to the research question. They are based on the enriched DFC representation and the PHARE. Two is dedicated to the structural similarity analysis, the other to assembly similarity analysis. Applications oriented to technical solutions have been introduced. Yet, space is left for future work, in particular concerning production system implementation or simulation to verify the application deductions and concerning the adding of investment evaluations.

Chapter V. Enabling the preliminary generation of alternative assembly plans

Based on the product models and similarity analysis presented in the previous chapters, this chapter is dedicated to the generation and comparison of preliminary assembly plans. First, a formalisation of precedence constraints is introduced. Next, a locating candidate identification approach is developed, based on the enriched DFC model. The locating candidates are key element for the preliminary assembly plan generation as the assembly system is seen as a sequence of locating modules (locating candidates with their operations). The precedence constraints and the locating candidate information is merged into a new product representation: the precedence-location graph. This representation allows either the generation of all assembly sequences or the application of locating module sequencing strategies and assembly operation sequencing strategies to restrain possible solutions. To compare the results, i.e. the preliminary assembly plans, a biological analogy with DNA is proposed to transform them to sequences for the application of LCS/SCS reasoning. It is used to analyse different preliminary assembly plans in terms of assembly sequence commonality (mutuality or differences of assembly units).

For the design of production systems, decisions made for the generation of assembly sequences are of high importance, as they define the architecture of the assembly system. The organisation of the system modules around component locations is seen as the key element for the design of assembly systems for a product variety and multi-product assembly. This new way of organising the production system is based on the components which are located in the modules for assembly. Focusing on these for the assembly system architecture design allows to identify compatibilities across the product portfolio and to organise assembly modules around these compatible locating components.

The classic dedicated thinking of assembly steps by considering *one* module for *one* operation with *one* component location for *one* product has to be overcome. Reconfigurable and flexible multi-product assembly systems should be based on the question: which sequence of mutual component locating is optimal to realise all assembly operations of all considered products with a minimum of changes?

To answer this question, a methodology for the generation of preliminary assembly plans is presented in this chapter. A preliminary assembly plan is the sequence of component locations with their operation sequences. The entire generation process is

presented in Figure V.1. It reaches up to a method to compare different preliminary assembly plans. As shown, the final selection of assembly plans (through evaluation, simulation, investment estimation, etc.) is not described in this document. All stages needed for the generation and comparison of preliminary assembly plans are described step by step in the following sections.

On the way to the sequence selection, at several points during the process, one is confronted to make decisions which have an impact on the outcome. In general, selection criteria can be added to restrain the number of generated solutions. This makes the selection step easier and reduces the efforts needed. These “decision” points are illustrated in Figure V.1. The first point where additional criteria can be applied, is the identification of extrinsic precedence constraints. Accessibility and operation constraints are considered as essential, but additional constraints may be added depending on the application or the company. Nevertheless, it is recommended to limit precedence constraints to a minimum to no restrain unnecessarily the solution space. The next decision is the pre-selection of locating candidates. At this point, industrial experience can be used to discard candidates which have been revealed problematic, to exclude them from the process.

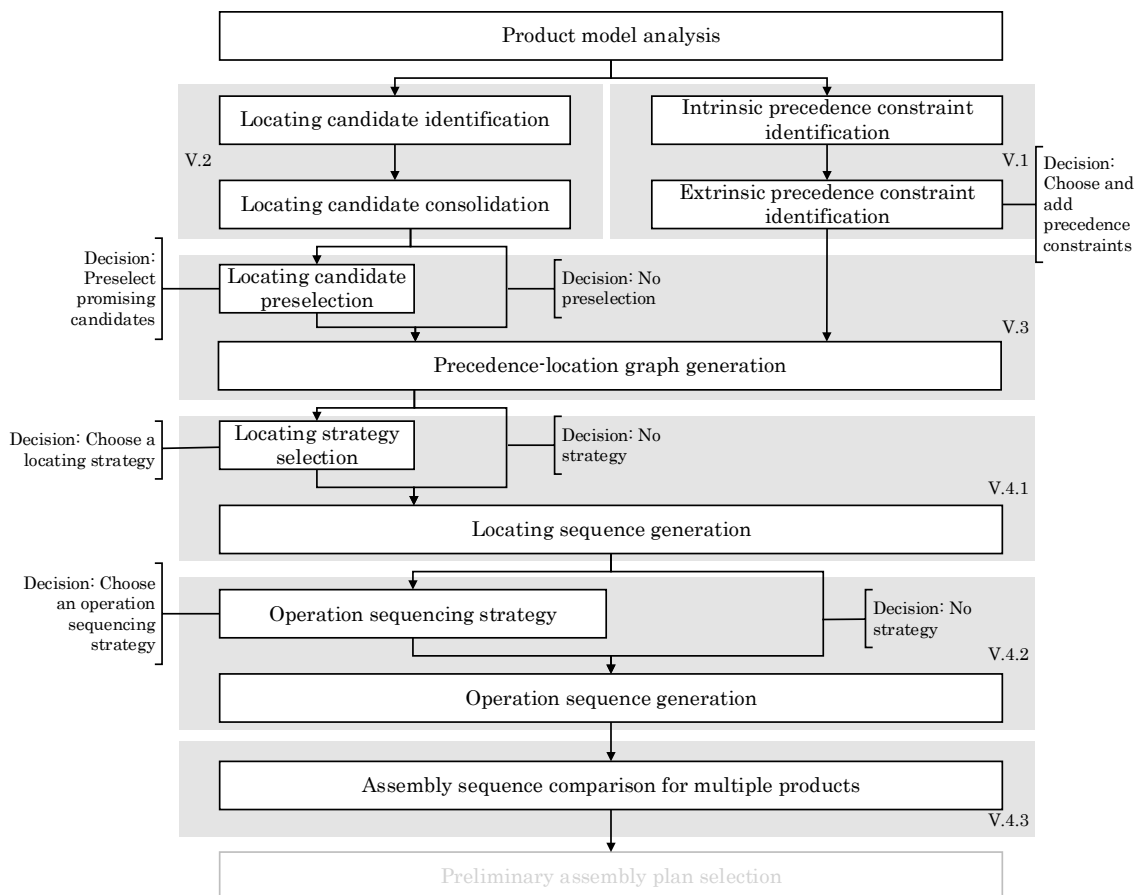


Figure V.1. General process for assembly sequence generation with decision options

Then, a strategy can be chosen for locating sequences: one oriented towards an assembly system with few modules gathering a lot of operations, and the other oriented towards module diversification. Finally, criteria can be applied for the sequencing of assembly and complementary operations in between a module.

The structure of the following sections, where the different models, tools and applications for the generation and comparison of preliminary assembly plans are described, is following the process presented in Figure V.1 and refers to the sections indicated for each topic.

V.1. Modelling assembly precedence constraints

Assembly precedence constraint definition is a preliminary step for the determination of assembly sequences and it is required to answer research aim 3.1. The literature review on precedence constraints highlighted that logical expressions are a universal model to define precedencies. In addition, they allow the combination of different precedence constraints, as for example operational constraints or accessibility constraints, as long as they can be expressed as logical operation. Some precedence constraints can be deduced automatically from the enriched DFC by pattern recognition.

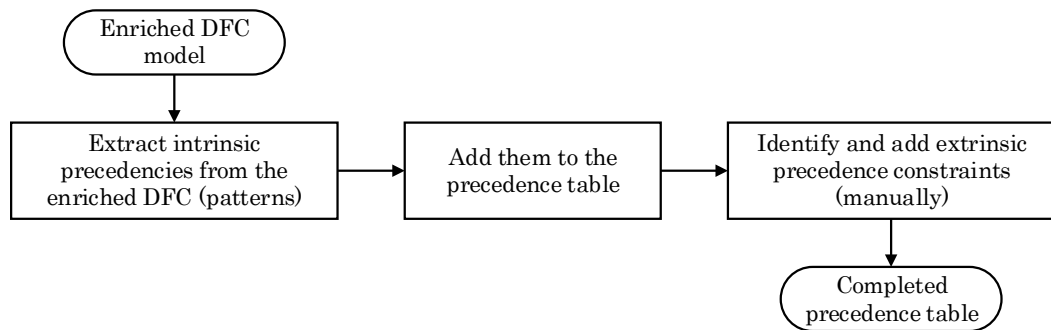


Figure V.2. Precedence constraint identification process

The Figure V.2 shows the global precedence constraint identification process. Precedence identification is based on the enriched DFC model, introduced in Chapter III. Based on this model, deducible (called intrinsic) precedence constraints are identified and added to the precedence table. Afterwards, all other precedence constraints (called extrinsic) are identified and also added to the precedence table. The expression of precedence constraints and the precedence table is presented in the following section. Intrinsic and extrinsic precedence constraints are described in detail in section V.1.2.

V.1.1. Logical expression of precedence constraints

The precedence constraints, as presented hereafter, list mechanical links which have to be realised before other ones. Logical expressions and connectors are used to define the precedence relations. The used operators are introduced in Table V.1. Combinations of these operators are used to express precedence constraints. The input of the precedence constraints is expressed in a table representing all mechanical links of the product. This table can be derived out of the enriched DFC model (see Chapter III for the model descriptions). Each line and column represents one component.

At the initial state, the table contains only entries equal to one if one component is linked to another one with an outgoing arc. All the other entries are equal to zero. Each entry being equal to one represents a mechanical link between two components.

Table V.1. Logical expressions for precedence constraints

Operator	Signification
x_n	Link denominator (n = running number)
$x_1 > x_2$	x_1 after x_2
$x_1 \gg x_2$	x_1 immediately after x_2
(...)	Grouping
\wedge	Connector AND
\vee	Connector OR
$x_1 x_2$	Simultaneous realisation of x_1 and x_2

This component table can be expressed in a matrix, here called **C**. Its entries are c_{ij} . By definition, the entries with $i = j$ must be zero as a component cannot have a link to itself. The objective is to identify the part relations for whom a precedence expression is possible.

$$C = \begin{pmatrix} c_{11} & \dots & c_{1j} \\ \vdots & \ddots & \vdots \\ c_{i1} & \dots & c_{ij} \end{pmatrix} \text{ with } c_{ij} = \begin{cases} 1 & \text{if part } i \text{ has an outgoing arc to part } j; \\ 0 & \text{else} \end{cases} ; \forall i, j \in \mathbb{N} \quad (V.1)$$

All entries which are equal to one, that means all existing mechanical links are needed to be analysed for precedence constraint analysis. This means that all entries equal to zero (it is also possible to leave the entries empty) can be ignored. During the input of the precedence information, successively the entries equal to one are replaced by a combination of precedence operators as illustrated in Table V.1. All entries without any precedence operator are independent mechanical links which are supposed to be realised at any moment during the assembly process. The precedence constraints are transitive, that means that if x_1 is before x_2 and x_2 is before x_3 , then x_1 is also before x_3 .

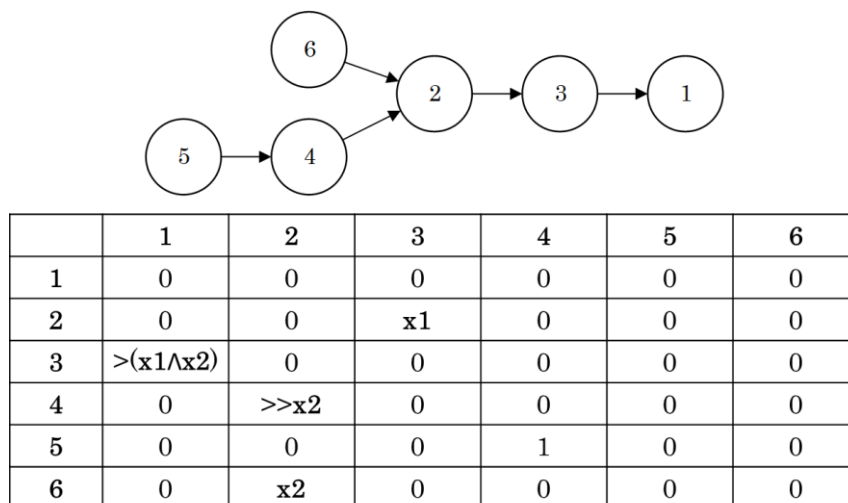


Figure V.3. Example for precedence constraint expression

Figure V.3 gives a short example for precedence constraint expression. Matrix **C** is represented as a table, the nodes and arcs of an exemplary enriched DFC (i.e. its components and mechanical links) are represented above the table. The components five and six do not have any entering arcs, which means that they are the starting point of the DFC model. The link from component five to component four has no precedence operators which indicates that it is supposed to be independent in the assembly. The mechanical link from component two to component three is named by x_1 , the mechanical link from component six to component two is named by x_2 . The precedence operators represent the following information: link from three to one after the realisation of x_1 and x_2 . And the link from four to two immediately after x_2 .

However, in addition to sequencing information, some mechanical links are realised simultaneously due to the product design. A procedure to identify those simultaneously realised mechanical links is presented by [Whitney 2004]. The procedure is based on the closure of subgraphs in the DFC and it is applicable to any subgraph. It defines that if at some point in an assembly process, a subgraph of n links remains with $n - 2$ links already made, then the next assembly step applied to that subgraph will realise both of the remaining open links.

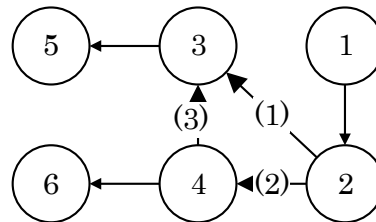


Figure V.4. Identification of simultaneously realised links

An example for the application of this procedure is illustrated with the small DFC in Figure V.4. A subgraph concerned is the bold subgraph between the components 2, 3 and 4 with the links (1), (2) and (3). It has three links. Applying the rule shows that if one link is realised, the other two are realised at the same time in a next step. For example, when link (1) is realised, the links (2) and (3) are realised simultaneously.

V.1.2. Determination of precedence constraints

The previous section defines how to express and read precedence relations. In this section the way to define precedence relations is introduced. As the enriched DFC model includes information about relative component positioning, it can be used for a preliminary identification of precedence constraints, following the chains of relative positioning propagation. This kind of information is called “intrinsic precedence constraints”.

Definition V.1: Intrinsic Precedence Constraints

Intrinsic precedence constraints are precedence constraints which can be derived out of the enriched DFC model by combining information about assembly technology with patterns of DFC subgraphs. The intrinsic precedence constraints can be deduced automatically. They represent precedence constraint due to relative locating and assembly technology constraints.

The patterns for precedence constraints are presented in the following. To identify the according precedence constraints, it is necessary to identify the patterns (subgraphs in the enriched DFC product model), combining information from both, subgraphs and assembly technology.

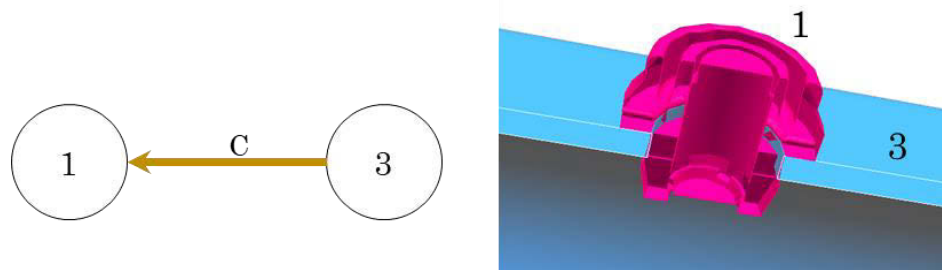


Figure V.5. Pattern 1 – The linear pattern

Figure V.5 illustrates the linear pattern, the most basic pattern: one component locates another component without any other interaction. The meaning is the realisation of accessory parts as illustrated in the figure (the example could be an oil drain plug or a stopper). The technologies which are allowed with this pattern are: placing-charging, welding-brazing, press-fitting and plating, riveting, clipping, marking, adhesive bonding, filling, and bolted assembly. The link which is included by this pattern has no particular precedence.

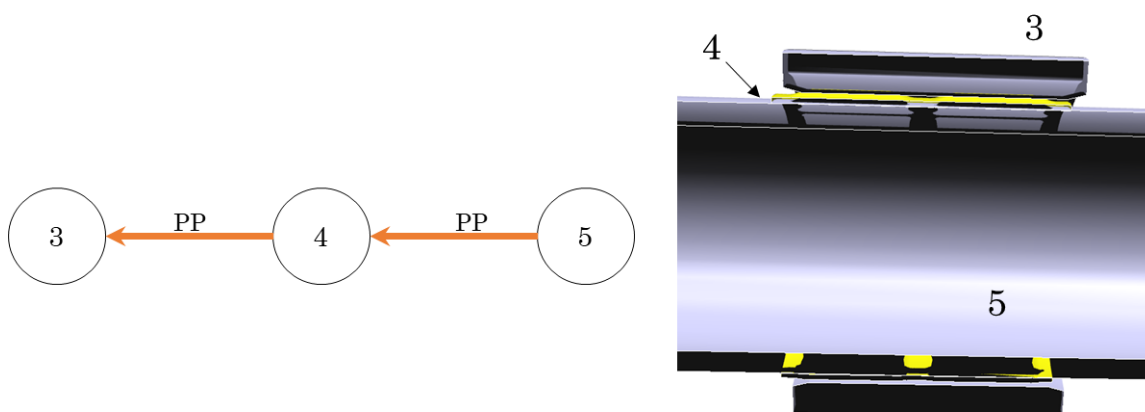


Figure V.6. Pattern 2 - The continued linear pattern

The continued linear pattern is illustrated in Figure V.6. It represents stacking components either radial around a cylindrical base part or lateral one above the other. The elements do not have more than two connections (one incoming and one outgoing). The example can be the press fitting (PP) of several parts on a shaft. The technologies: placing-charging, welding-brazing, press-fitting and plating, riveting, clipping, marking, adhesive bonding, filling, and bolted assembly are allowed with this pattern. Similar to the first pattern, no specific precedence constraints exist due to the locating and assembly technology information. Each link can be realised independently to the others. However, in some special cases, a precedence sequence may be imposed, starting with the base part and go to the final component. In the figure, the link sequence would be $\{2-3 > 4-2 > 5-4\}$.

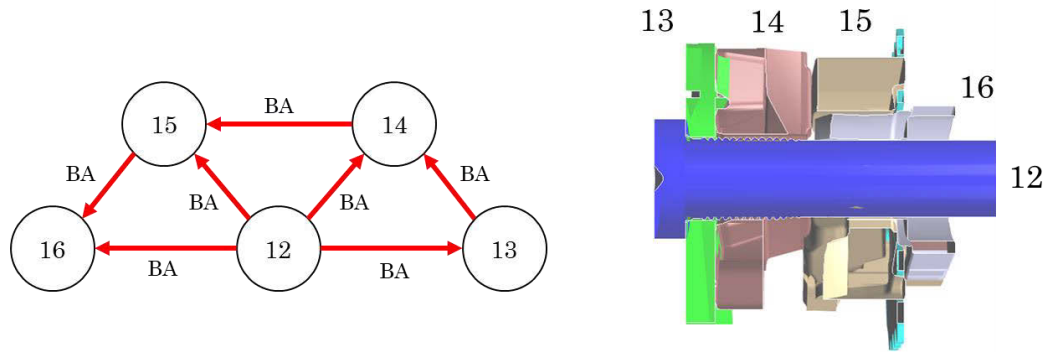


Figure V.7. Pattern 4 - The circular pattern

Figure V.7 illustrates the circular pattern, called like this because it develops its mechanical links describing a circle around a centred part. It is dedicated to assemblies using bolts, representing the stacking of parts on the bolt. Therefore, the allowed assembly technologies are bolted assembly and riveting (when using the rivet as bolt). The precedencies are following the direction of the arcs. In the example in Figure V.7, the link precedencies would be $\{12-n|15-n > 12-15|14-15 > 12-14|13-14 > 12-13\}$. The links which are separated by the vertical separator “|” are realised at the same time respecting to the subgraph closure rule. As stacking parts on a bolt is rarely a stable assembly, the precedence operators can be changed from normal precedencies (“>”) to immediate precedencies (“>>”).

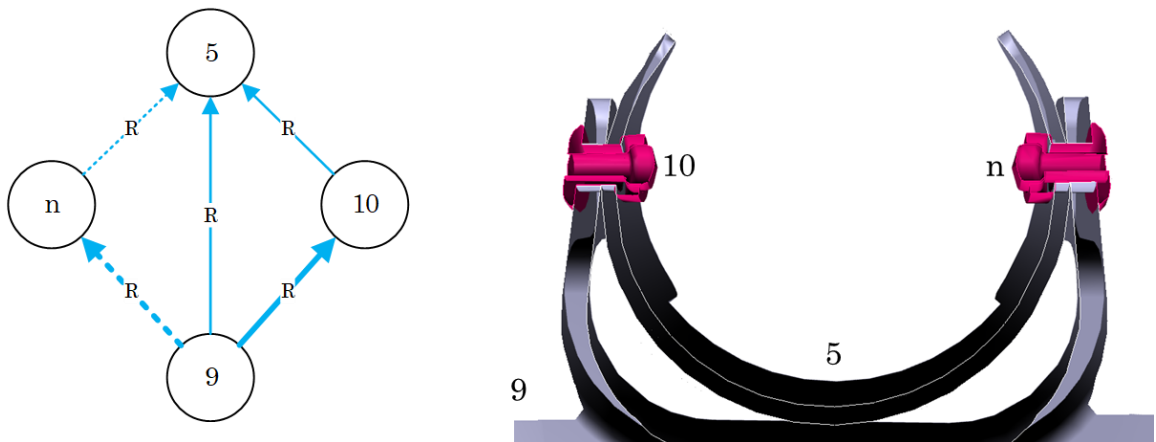


Figure V.8. Pattern 4 – The trapezoid pattern

Finally, the fourth pattern is the trapezoid pattern as illustrated in Figure V.8. It represents the assembly of components with connector elements (in general screws or rivets). In the example, it is two sheets with three rivets. The precedencies follow always the sequence that the two elements to assemble must be positioned before putting the connector elements. In the example it is $\{9-10|10-5 > 9-5; 9-n|n-5 > 9-5\}$. The two sheets are positioned at first. Afterwards, the connectors are assembled but no precedence exists between the connector elements themselves.

However, the intrinsic precedence constraints, which have been presented in this section, are not representing all precedence constraints. To cover this gap, “extrinsic precedence constraints” which are not deducible from the enriched DFC, have to be defined.

Definition V.2: Extrinsic Precedence Constraints

Extrinsic precedence constraints are all precedence constraints which cannot be derived automatically out of the enriched DFC model. They are extrinsic to the product model.

Extrinsic precedence constraints regroup all precedence constraints that are judged necessary to assure that the assembly sequences generated can be realised. Two precedence constraint types, the most essential ones, are defined below. The list claims not to be exhaustive and the importance of particular precedence constraints in regard to other may change between industrial domains and companies.

Accessibility constraints: These are the most essential precedence constraints as they assure that the mechanical links can be realised by granting that all zones of the (sub)assembly which are concerned are accessible by the component and tools.

Operation constraints: These are constraints which restrain certain operation sequences as they can alter the quality of the product. Classically, they concern assembly operation affecting the (sub)assembly with thermal treatments as heating or welding and brazing operations. For example, no welding operation should be done close to assembled bearings as the thermal induction effects the maintain and the quality of the bearings. In this case, the welding operation has to be done before assembling the bearing. These constraints can also concern operations having a risk of being unsuccessful which means that they can lead to the reject of the product due to insufficient quality.

In the presented precedence model, the extrinsic precedence constraints have to be added manually to the precedence table. They must be identified by an industrial expert.

Example V.1: Precedence constraint identification for a feather pen

The DFC model with assembly technologies is reminded in Figure V.9. Two different patterns could be identified: the linear pattern and the continued linear pattern.

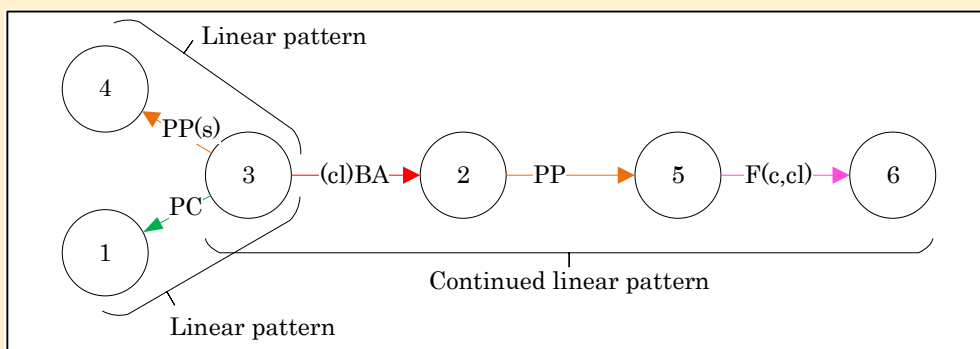


Figure V.9. Reminder - Ball pen DFC with assembly technologies and patterns

According to the definitions introduced before, no specific precedence constraint is linked to the locating and assembly information contained in the enriched DFC. The accessibility analysis results in the set of precedence constraints illustrated in the precedence table in Figure V.10.

bp	1	2	3	4	5	6
1	0	0	0	0	0	0
2	0	0	0	0	x2	0
3	>x3	>(x1∧x2),x3	0	1	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	x1
6	0	0	0	0	0	0

Figure V.10. Precedence table for the ball pen (bp)

The link 5-6 is denominated x_1 , the link 2-5 is denominated x_2 and the link 3-2 is denominated x_3 . As no additional operational constraints have to be added, the precedence table for the ball pen is complete and finished. The assembly steps as identified are the following:

- (1.1) Fill ink into the cartridge
- (1.2) Press cartridge on the head
- (3) Insert cartridge and head into the body
- (4) Put cap on the body

At any moment: Fix plug on the body

The operations (1.1) and (1.2) must be realised before operation (3) but do not have a precedence in between themselves, supposing that the ink can still be filled in when the cartridge is connected to the head.

V.2. Identifying locating candidates

After the precedence constraint identification, the next step towards the definition of assembly sequences is the identification of candidate components for locating (sub)assemblies of the product. The industrial problem is how to define assembly sequences and how to design a multi-product assembly line for product varieties. In this context, the identification of locating candidates is a key component for the assembly sequence generation as they are considered to be the enabler (or discriminant element) for multi-product assembly. This makes locating candidates also an important element for the application of assembly sequence strategies.

Definition V.3: Locating candidate

A locating candidate is a component of the product or one of its subassemblies which can be a base part for other assemblies. That means a locating candidate is a component which is at the beginning or the end of a sequence of mechanical links which can be assembled by putting into position the locating candidate.

However, the literature review showed that no work on locating strategies for multi-product assembly has been realised yet. The literature is mainly manufacturing oriented and proposes highly specific applications. Therefore, a new methodology to identify the locating candidates is introduced in the following section which responds to the challenges of research aim 3.2.

V.2.1. A methodology for the identification of locating candidates

Candidates for locating are components which could be used as base parts for assemblies and subassemblies. An identification process for those candidates, based on the enriched DFC, is introduced in this section. As functional subassemblies have been introduced as subdivisions of the product and granularity level for similarity analysis and product comparison, the locating candidates are identified considering each functional subassembly.

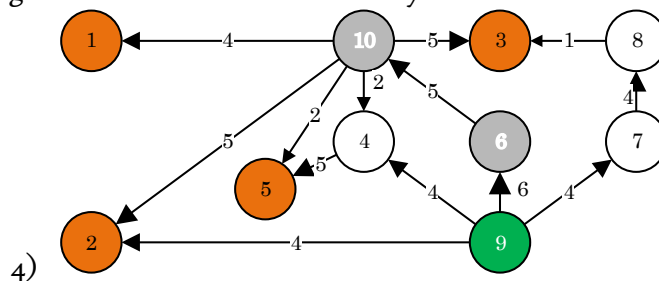
The hypothesis is that a locating candidate has to be situated either in the beginning or at the end of a locating propagation chain in the Datum Flow Chain. This means that the components which are supposed to be in the beginning or at the end of an assembly sequence are supposed to be candidate for positing their belonging assembly during the assembly process. The assembly sequences describe the completion of mechanical links. Thus, the enriched DFC, by displaying all mechanical links contains implicitly their sequences.

The enriched DFC is therefore used to identify possible candidates for locating during the assembly process. The identification uses the source and sink theory introduced by [Marguet 2001]. It is modified to current application: the sink and source identification is adapted to the enriched DFC model. To do so, the following terms are used:

- The outdegree of a vertex describes the number of outgoing arcs and is noted $deg^-(v)$ with v being the vertex number.
- The indegree of a vertex describes the number of incoming arcs and is noted $deg^+(v)$ with v being the vertex number.

An application of the source and sink theory in the context of locating candidate identification has never been realised before. For this, a new procedure is introduced, based on three analysis steps of the enriched DFC, which are:

- 1) First, the identification of sources and sinks. In this case, a vertex with the indegree $deg^+(v) = 0$ is called a source, as it is the origin of each of its outgoing edges and a vertex with the outdegree $deg^-(v) = 0$ is called a sink, because it is the end of each of its incoming edges.
- 2) Second, the identification of vertices where $deg^-(v)$ is importantly higher than $deg^+(v)$ and with a high number of connections in general.
- 3) And thirdly, all vertices which are connected to a locating candidate by an edge having all degrees of freedom eliminated by the mechanical link).



5) Figure V.11. Example for sinks and sources expressed in a DFC graph

The illustration Figure V.11 helps to understand the concept. First, a source, i.e. a vertex with $deg^-(v) = 0$, is searched. Vertex 9 with $deg(9) = (0,4)$ is identified. It is the green vertex in the example graph. The reason to choose these kinds of vertices is linked to their meaning in the enriched DFC: a source vertex with $deg^-(v) = 0$ represents a

component which positions other parts, but which is itself not positioned relatively to any other component. This characteristic makes it a natural candidate for locating and a candidate for the starting point of an assembly sequence.

Then, as sinks, the vertices 1, 2, 3 and 5 are identified. They are the orange vertices in the example graph. Similar to the sources, the sink vertex with $\text{deg}^+(v) = 0$ represents a component which do not locate any other part, and which is therefore a possible ending point for an assembly sequence.

Finally, a vertex with $\text{deg}^-(v) \gg \text{deg}^+(v)$ is found, representing an important component due to its connectivity in the graph. It is vertex number 10 with $\text{deg}(10) = (1,5)$. This vertex is grey in the example graph. Vertices with the characteristic $\text{deg}^-(v) \gg \text{deg}^+(v)$ represent components locating more components than being located: they could be called dominating parts following the definition of dominating vertices in graph theory. These dominating components play an important role in the assembly process as they ensure the most connections to other components, a fact which makes them possible candidates for locating.

Finally, all vertices having a connection with the weight of 6 to candidates identified are also eligible as locating candidates as they represent components which have a fierce mechanical connection with one of the candidate components. As additional candidate, component 6 can be considered in Figure V.II. It is connected to vertex 9 with an edge of the value six, which means that both components are connected by eliminating all degrees of freedom between them.

The locating must be supported by available surfaces of the identified components. Available surfaces are the surfaces which will not be used to locate components during the product assembly process. As mentioned in the beginning of the section, the locating candidates are identified by functional subassembly. Analogous to the analysis of assembly technology similarity, also for the locating candidate identification there are locating candidates internal and external to a functional subassembly. Figure V.12 illustrates the three possible configurations. In this figure, internal sources are in dark green, external sources in light green.

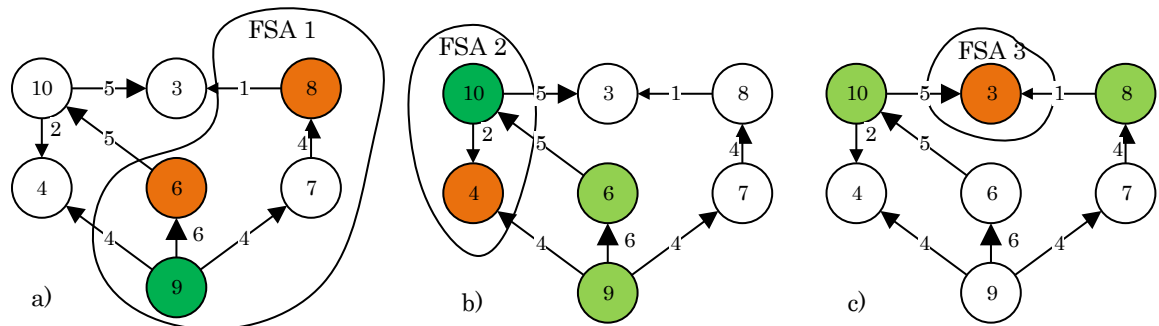


Figure V.12. Different configurations of internal and external sinks and sources

In configuration a), there are only internal sinks and sources as no incoming are exists for FSA 1. The according locating candidates for this FSA are component nine, six, and eight. In configuration b), both, internal and external sources exist as FSA 2 is positioned by entering arcs. In this configuration, the locating candidates are the components four and ten (internal) and nine and six (external). Finally, configuration b) gives an example for an FSA having only external sources. The locating candidates for this FSA are the components three (internal), ten, and eight. The example

highlights an important detail: redundancies are allowed, i.e. components can be locating candidates for multiple FSA and one mechanical link can have several locating candidates.

V.2.2. Identification of assembly relevant functional subassemblies

In Chapter IV, a framework for technical functions and their realisation in functional subassemblies of the product have been introduced. The derived product model is the PHARE representation. This model contains always the same number of technical functions for all products which means that the matrices have all the same size. It provides a same functional reference for products. This characteristic is important for similarity analysis applications as described in Chapter IV. However, as functional subassemblies can be included or identic to others, or can be not realised, the initial PHARE representation has to be modified to represent only the FSA which are relevant for assembly. These are called in the following “*relevant assembly FSA*”. The belonging representation is called the assembly-oriented PHARE.

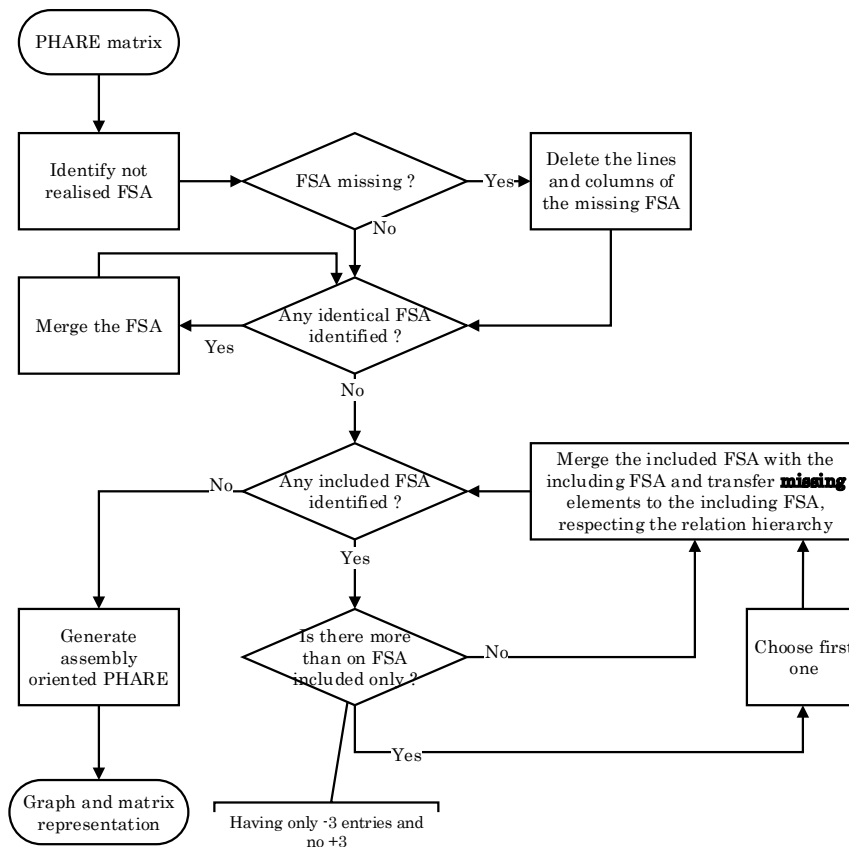


Figure V.13. Methodology for the generation the assembly-oriented PHARE

The methodology proposed to generate the assembly-oriented PHARE is illustrated in Figure V.13. It is based on the PHARE matrices. The first step consists on eliminating all FSA which are not realised, i.e. the FSA whose entries are all equal to zero, by deleting the belonging lines and columns. Not realised FSA are not considered for assembly and are therefore not necessary for this analysis. In a second step, identical FSA are merged. It means that their lines and columns are merged in the PHARE matrix. If several FSA are identic, it implies that the assembly of one of them covers all the other at the same time. Thus, only one of the identic FSA is kept to eliminate

redundant information. Last, all FSA included to another one are merged with their including ones. If an FSA is included in more than one other FSA it has to be merged with all of them. The FSA which includes the others become “super”-FSA. Differing information has to be added to the super-FSA. This concerns in particular information about *contact* relations as they are only linked to the included FSA but not the including ones (see also the five rules of PHARE generation presented in Chapter III). Adding the differing information must meet the hierarchy of PHARE relations, that means a weaker relation cannot overwrite a stronger relation.

$$\begin{aligned}
 \text{FSA 2 : } & (0|-1|-3| 0|-1| -1|-3|-3|-1| 0|-1| 0| 0|-3| 0|-1| 0|-1) \\
 \text{FSA 1 : } & (0|-1| 0|-3| 0| 0| 2| 2| 2|-3| 0| 3|-1| 2| 0| 2| 0| 0) \\
 \text{FSA 1\&2 : } & (0|-1| 0|-3|-1|-1| 2| 2| 2|-3|-1| 3|-1| 2| 0| 2| 0|-1)
 \end{aligned}$$

Figure V.14. Example of FSA merging

The Figure V.14 illustrates the line merging of FSA 2 to FSA 1. The same has to be done with the FSA columns in the PHARE matrix. The *contacts* are transferred to FSA 1 if the entries in FSA 1 are empty (green values) but not if the entries are occupied (red values). Entries representing *inclusions* (-3) are not transferred as they disappear along the merging process. The final assembly oriented PHARE representation has only relations of the type *partition* and *contact*. The structure of the assembly oriented PHARE is used in a last step to update the FSA of the enriched DFC representation. The latter is used for the identification of locating candidates, using the updated information about relevant assembly FSA coming from the assembly oriented PHARE.

Example V.2: Assembly-oriented PHARE of the ball pen

The initial PHARE of the ball pen is represented in the following matrix. The FSA are represented in increasing order by the lines and columns, i.e. FSA 1 in line 1 and column 1, ...:

$$\mathbf{P}_{bp} = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 3 & 0 \\ -1 & 0 & -3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

According to the methodology illustrated in Figure V.13, the not realised FSA are eliminated at first. In this case, it concerns FSA 5 (line and column 5). The new matrix after the first iteration is:

$$\mathbf{P}_{bp} = \begin{pmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & 2 & 0 \\ 0 & 2 & 0 & 3 \\ -1 & 0 & -3 & 0 \end{pmatrix}$$

No identity is present in the matrix, so the next step is merging the inclusions. In this case, FSA 4 (having -3) must be merged into FSA 3 (having +3). The contact entry of FSA 4 is moved to FSA 3; the concerned entries are marked in red with arrows. The inclusion entry disappears as the inclusion has been processed. The new matrix is:

$$\mathbf{P}_{bp} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 2 \\ -1 & 2 & 0 \end{pmatrix}$$

The matrix represents therefore FSA 1, FSA 2 and FSA $\frac{3}{4}$ with FSA 3 as super-FSA. The according assembly oriented PHARE is illustrated in Figure V.15.

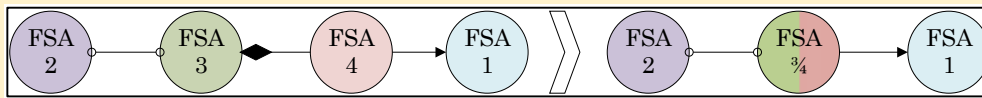


Figure V.15. Assembly oriented PHARE graph (right) and initial PHARE graph (left) of a ball pen

The according enriched DFC containing only assembly relevant FSA is illustrated in the Figure V.16.

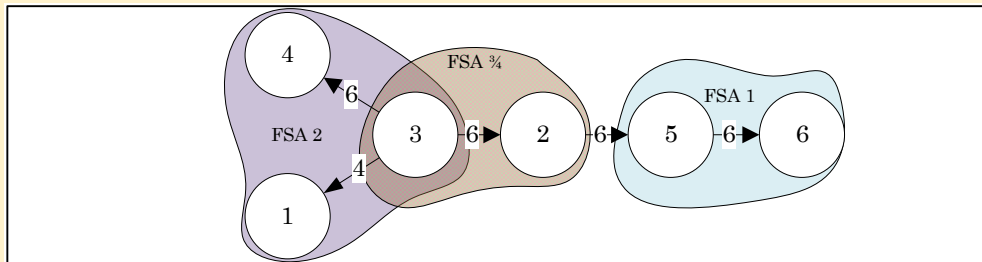


Figure V.16. Enriched assembly oriented DFC of a ball pen

V.2.3. Input and information gathering for locating candidates

The precedent sections have introduced a methodology to identify locating candidates and to determine relevant assembly FSA. In this section, the information concerning locating candidates is added to the assembly process information framework presented in Chapter III. As illustrated in Figure V.17, the enriched DFC is located on the level of assembly technology and link attributes as it displays this information. Out of the enriched DFC, with the application of the sink and source theory, locating candidates are identified. These are transversal over all the categories of the taxonomy. It means that locating candidates are defined for mechanical links considering assembly processes by assembly technology and link attributes with their respective operations and parameters. This means that the entire information concerning assembly processes is linked to the information about locating candidates.

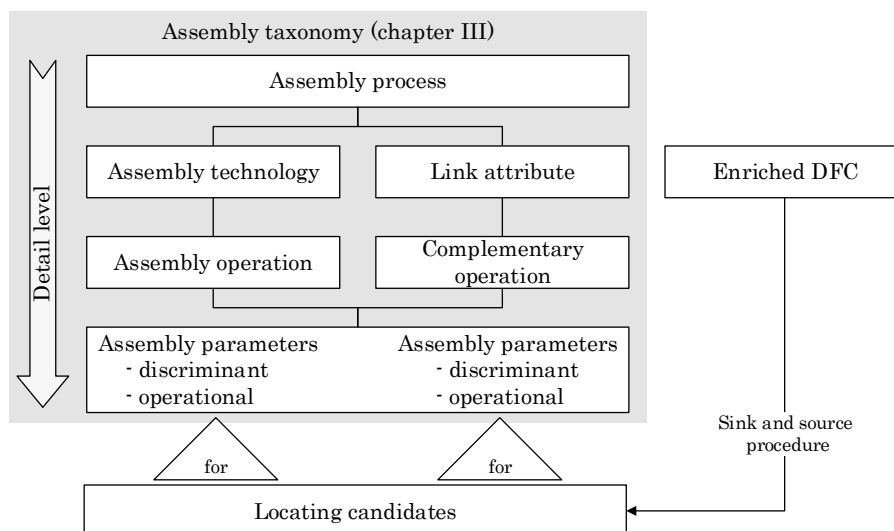


Figure V.17. Assembly process taxonomy with locating candidates

In practical applications, the locating candidates are added to the generic template for assembly information gathering. The generic template is applied to each of the relevant assembly FSA. The locating candidates which have been identified with the sink and source method are added in the new boxes (9.1) and (9.2), illustrated in Figure V.18. All information is inserted only for the links which are concerned by the examined FSA: these are the internal links and the entering links. The latter are considered because they carry information of how the FSA components are positioned relatively to the others and they are essential in the case that an FSA has no internal arcs.

The boxes (9.1) and (9.2) gather the information whether a mechanical link can be realised in regard of a locating candidate or not. They can be seen as locating candidate – mechanical link allocation matrices. To determine if a locating candidate is suited for the realisation of a mechanical link, three criteria have to be analysed: “accessibility and orientation”, “degrees of freedom of the mechanical link” and “force”.

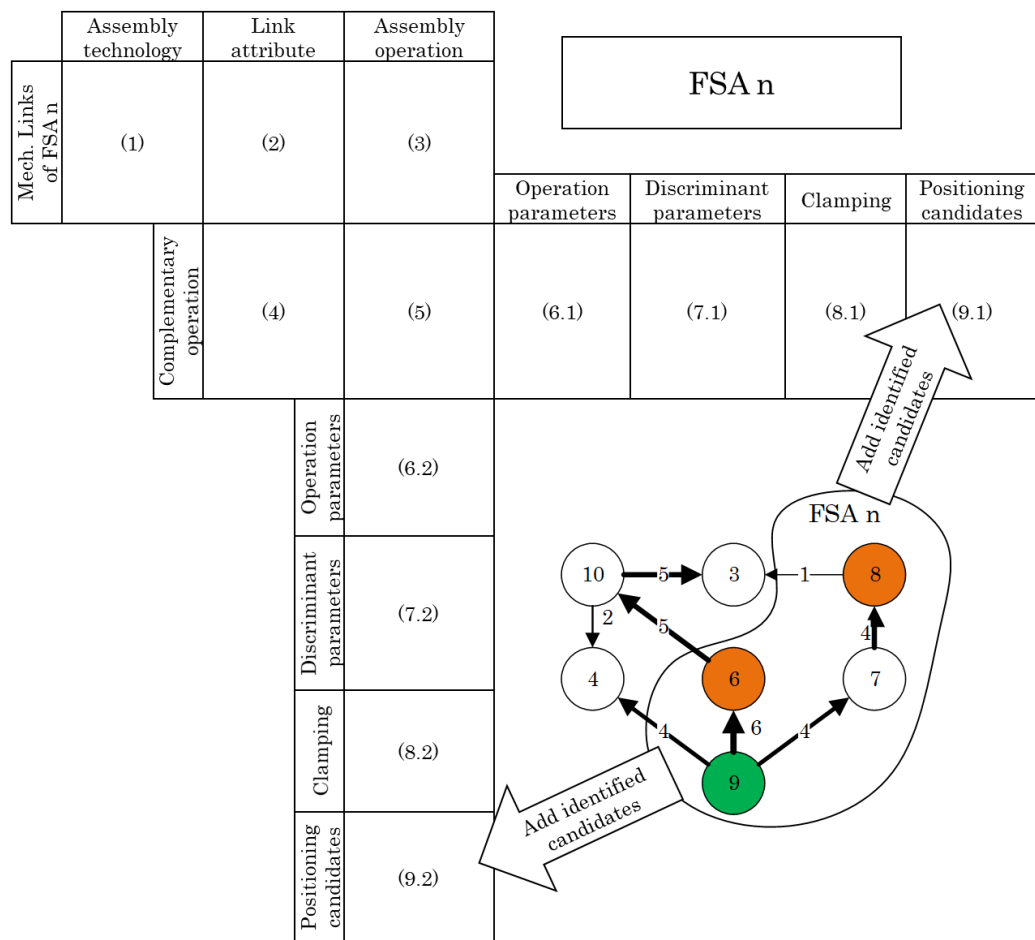


Figure V.18. Assembly technology and locating candidate information gathering template

The accessibility and orientation criterion defines if assembly operations (the realisation of edges in the graph) are possible. This is not the case if the locating blocks the tool and component trajectories.

The degree of freedom criterion defines whether an assembly operation achieves a stable subset or not. If a connection achieves too few degrees of freedom the connection realised is not stable and therefore is not feasible. Parts could fall apart during transfer or assembly operations.

All connections from a locating candidate are feasible if they are not contradictory to these criteria. However, the candidates identified on this way are theoretic and may not be ideal in a real environment. The aim is to identify the minimum number of different locating candidates for a product assembly. Ideally, it exists one locating candidate which enables the realisation of all assembly steps, i.e. a universal locating candidate for an entire assembly. This one can be called an ideal locating.

After the identification of all candidates, they have to be divided into possible candidates for further consideration or impossible candidates which should be discarded. This evaluation has to be done by an industrial expert.

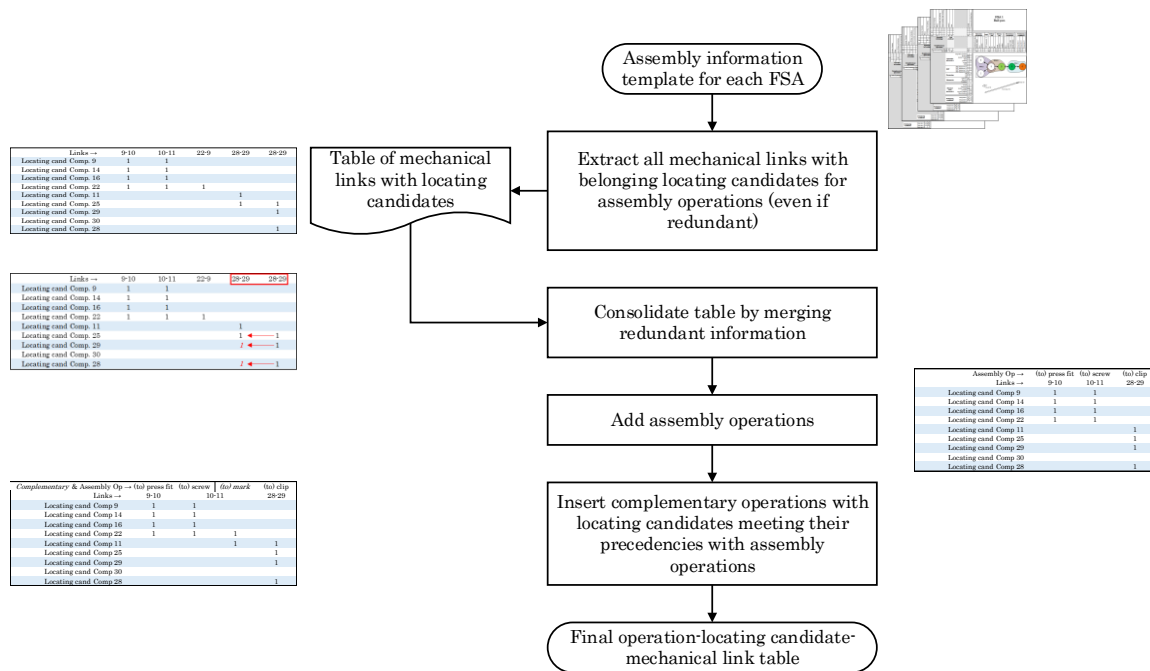
V.3. Combining precedencies and locating information to formalise assembly sequences based on locating strategy

On the way to the preliminary generation of possible assembly sequences, a new modelling approach is needed to combine the locating information with the previously determined precedence information. For instance, the data is formalised and stored in two different files: the locating information is gathered into the assembly information template and the precedence constraints are added to precedence constraint tables. The representation of information differs slightly. In the assembly information template, the mechanical links are indicated explicitly, in the precedence table they remain implicit. Information about operation precedencies (complementary vs assembly) are stocked in the assembly information template and not in the precedence table. Therefore, to enable the processing of both, precedencies and locating candidate information, both information types have to be extracted, consolidated and translated into a generic model of mechanical link precedencies with locating information. This is described in following sections, representing the merging of the research aims 3.1 and 3.2, in order meet the requirements of research aim 3.3.

V.3.1. Consolidation of locating candidates and operations

The assembly information template, by its analysis of mechanical links for each relevant assembly FSA, may contain redundant information concerning mechanical links and split up information concerning locating candidates. This means that some mechanical links are repeated in different tables, but for each of the tables, the identified locating candidates may differ. For the consolidation, a multi-step procedure is applied. Its illustration is available in Figure V.20. The actions for consolidation are explained in the following:

- First, a table is generated which gathers on the lines information about locating candidates for assembly operations (box 9.2 in the template) and on the columns the mechanical links of the product. Redundancies are eliminated in this table by merging table columns;
- Second, information about complementary operations and their precedencies (if there are) in regard to assembly operations is added to the consolidated locating candidate table. In the first step, assembly operations are added. Then, complementary operations are added. If they have to be realised before an assembly operation, they are added immediately before it. Analogously, if they are realised after an assembly operation. Finally, the locating candidate information is completed with information out of box 9.1.



A zoom on the elements is provided in the next figures.

Figure V.20. Locating candidate consolidation process

In the table of mechanical links with locating candidates, the redundant locating candidate information is consolidated. Figure V.21 illustrates an excerpt of a locating candidate consolidation table. The redundant entries have been extracted from different assembly information templates (for different FSA of the same product). The redundant columns and their entries are merged as illustrated by the arrows.

Links →	9-10	10-11	22-9	28-29	28-29
Locating cand Comp. 9	1	1			
Locating cand Comp. 14	1	1			
Locating cand Comp. 16	1	1			
Locating cand Comp. 22	1	1	1		
Locating cand Comp. 11				1	
Locating cand Comp. 25				1	← 1
Locating cand Comp. 29				1	← 1
Locating cand Comp. 30					
Locating cand Comp. 28				1	← 1

Figure V.21. Example for locating candidate consolidation

Complementary & Assembly Op →	(to) press fit	(to) screw	(to) mark	(to) clip
Links →	9-10	10-11	28-29	28-29
Locating cand Comp 9	1	1		
Locating cand Comp 14	1	1		
Locating cand Comp 16	1	1		
Locating cand Comp 22	1	1	1	
Locating cand Comp 11			1	1
Locating cand Comp 25				1
Locating cand Comp 29				1
Locating cand Comp 30				
Locating cand Comp 28				1

Figure V.22. Illustration of the final operation-locating candidate-mechanical link table

An illustration for the final table is given in Figure V.22. The box indicates where a complementary operation has been added. The order emphasises that the assembly

operation ((to) screw) is realised before the complementary operation ((to) mark). Both operations concern the mechanical link between the components ten and eleven. In the example, the locating candidates for the assembly operation are not all suited for the complementary operation, and the latter has an additional locating candidate.

Example V.4: Locating candidate consolidation for the ball pen

The generation of the consolidated table regrouping locating candidate, assembly operations and complementary operations is illustrated in Figure V.23.

Links →	3-1	3-4	3-2	2-5	5-6				
Locating cand Comp 3	1	1	1						
Locating cand Comp 1	1								
Locating cand Comp 2			1	1	1				
Locating cand Comp 5				1	1				

Assembly Op →	(to) introduce	(to) press fit wf	(to) screw	(to) press fit wf	(to) fill				
Links →	3-1	3-4	3-2	2-5	5-6				
Locating cand Comp 3	1	1	1						
Locating cand Comp 1	1								
Locating cand Comp 2			1	1	1				
Locating cand Comp 5				1	1				

Complementary & Assembly Op →	(to) introduce	(to) press fit wf	(to) seam	(to) clean	(to) screw	(to) press fit wf	(to) fill	(to) control presence	(to) clean
Links →	3-1	3-4			3-2	2-5		5-6	
Locating cand Comp 3	1	1	1		1				
Locating cand Comp 1	1								
Locating cand Comp 2				1	1	1	1	1	1
Locating cand Comp 5						1	1	1	1

wf = without force

Figure V.23. Illustration of locating candidate consolidation for a ball pen

The assembly and complementary operations are consistent to the ones which have been defined in Chapter III, and as described in that chapter, one operation is defined or each mechanical link. Due to the simple assembly, no redundant information has been extracted out of the information gathering templates.

V.3.2. Merging precedence constraints with locating candidates

The merging of precedence constraints with locating candidates results in a precedence-locating graph, illustrated in Figure V.24. Its generation process is illustrated in Figure V.25. The precedence graph is defined with nodes being the mechanical links and arcs being the precedence information. If two operations are realised at the same time, they share the same node.

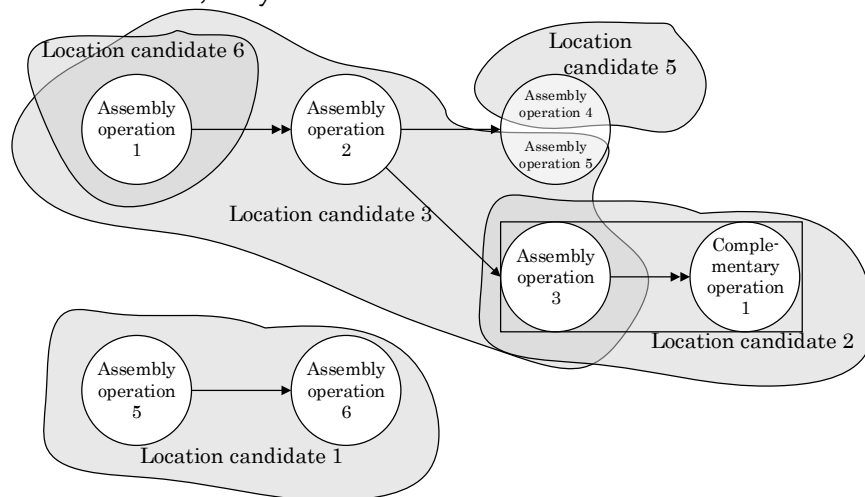


Figure V.24. Schematic illustration of the precedence-locating graph

The design of the graphical representation itself is consistent with the enriched DFC representation. Complementary operations are attached to their assembly operations by a rectangular frame. It gathers all operations carried out on the same mechanical link. Three different precedence information are displayed: no precedence (no arc), standard precedence (arc with single arrow) and immediate precedence (arc with double arrow). Subassemblies being independent in terms of precedencies are represented by non-connected graphs. Thus, one product assembly can be represented by several unconnected graphs if its subassemblies are not linked by precedence constraints. Locating possibilities are represented by zones covering the nodes of the precedence graph. The allocation of operations to locating candidates is called *location module*. Each zone stands for one locating candidate.

Definition V.4: Location module

A location module (also: locating module) is the combination of locating candidates with operation or operation sequences. All operations which are located in between a location module are supposed to be realised using the same locating candidate. In a locating oriented assembly systems, locating modules may also represent its assembly modules.

A special case occurs, when a node including two or more parallel operations has different locating candidates (as illustrated with locating candidate in Figure V.24). In this case, two possibilities exist: one of the locating candidate can be used for all operations if the assembly allows it. Or the two operations have to be carried out using both locating candidates at the same time, as they are parallel operations.

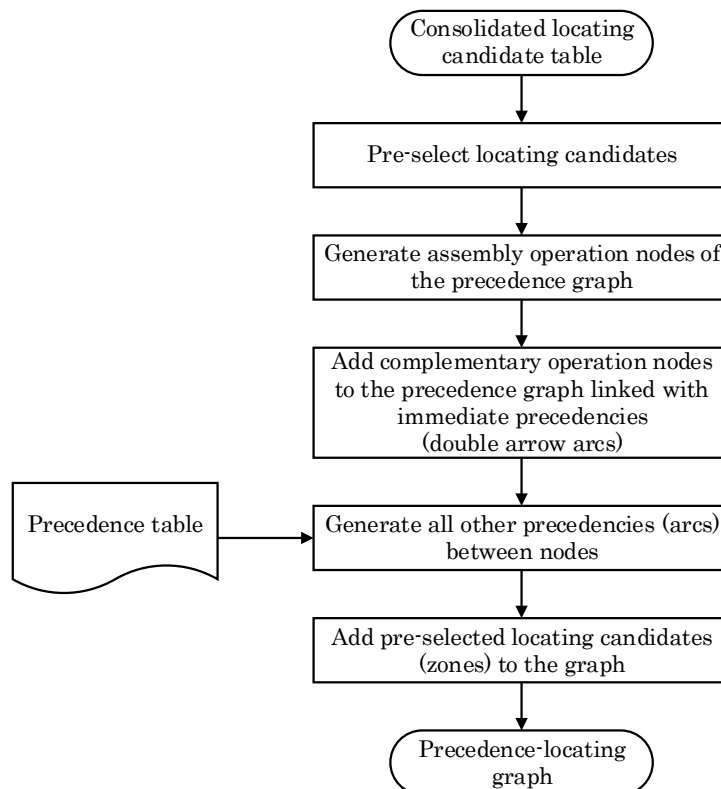


Figure V.25. Precedence-locating graph generation process

The locating candidate zones as well can be independent, overlapping or included. Overlaps means that different possibilities for locating exist. One may choose only one

of the possible locating candidates or use a combination of locating candidates. The generation of a precedence-location graph is illustrated in the following example.

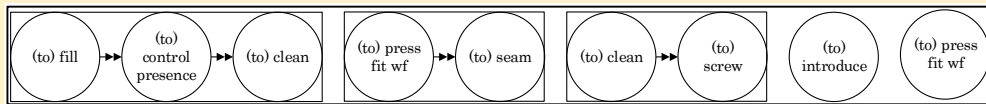
Example V.5: Precedence-locating graph of the ball pen

Referring to Figure V.25, the first step in the precedence-locating graph generation is the pre-selection of locating candidates. For the ball pen, two possibilities exist: to select the minimum number of candidates needed for assembly (components 1 and 2). Or to select also additional candidates having a lot of surface available for positioning (components 1, 2, and 5).

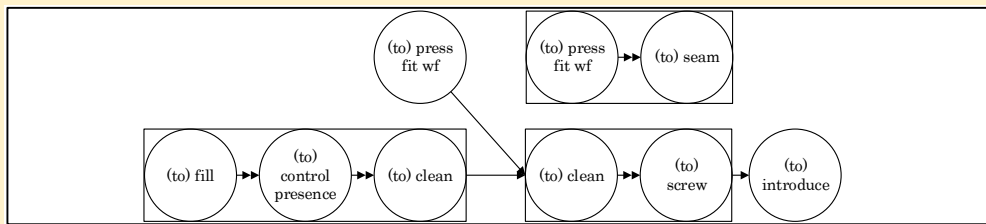
In the next step, the assembly operation nodes are added to the graph:



Then, complementary operations are added, linked with immediate precedencies:



Third, all other precedencies are added (see precedence table of the ball pen):



Last, locating candidates are added:

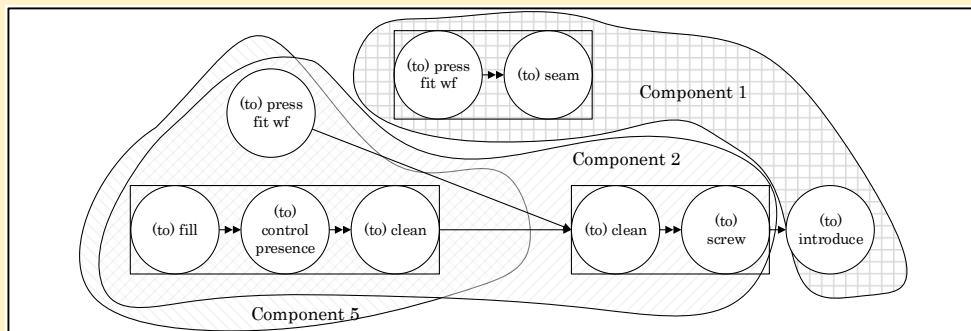


Figure V.26. Ball pen precedence-locating graph

The precedence-locating graph has been generated. For the example in Figure V.26, the three locating candidates 1,2 and 5 have been considered. The graph illustrates that this decision offers a choice possibility for the assembly sequence generation between component 5 and component 2 (overlapping zones).

When merging precedence constraints with locating candidates, a preselection can be made at this stage. Different possibilities are offered at his step: One may choose all candidate, or only the minimum number of candidates to realise an assembly. Or one may pre-select candidates based on criteria like material or available surface for fixtures. To realise a selection based on criteria, the candidates need to be classified. To

do so, common multi-criteria evaluation methods can be applied to assign a score on the different locating candidates and to support multi-criteria decision making.

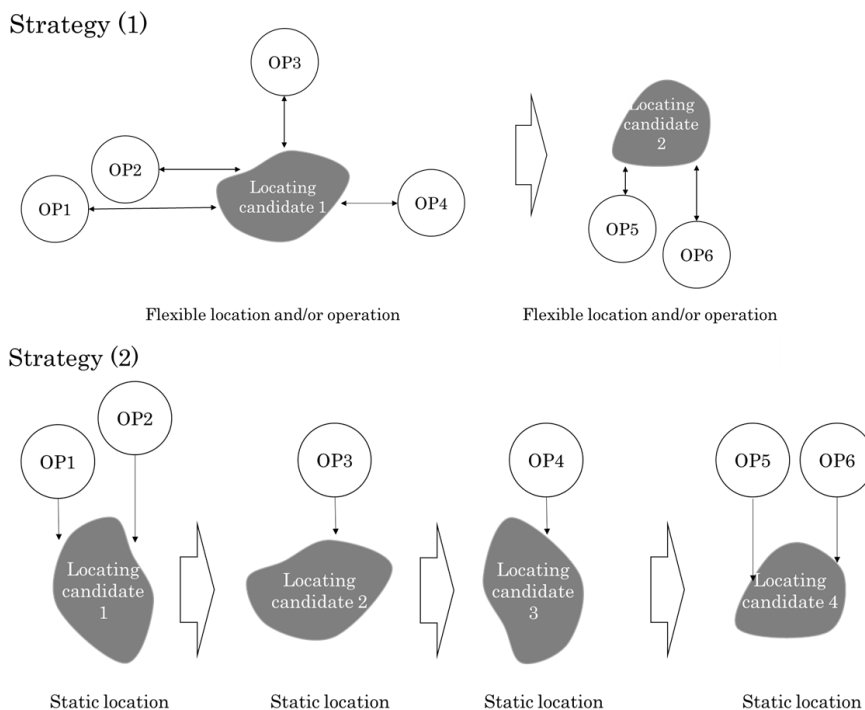
V.4. Enabling the generation and comparison of assembly sequences for a product family

As mentioned in the introduction, the generation of assembly plans for multi-product assembly systems for a product variety should be guided by the choice of a mutual locating module sequence. To generate assembly plans based on locating modules, the previously introduced precedence-locating graph is used as starting point. Based on it, either all possible sequences, or pre-selected sequences by the application of sequencing strategies and criteria can be generated.

V.4.1. Applying location sequencing strategies

The first step of applying strategies is the choice of a location system. This choice determines the macroscopic structure of the production system. Two different philosophies are identified and presented in the following:

- (1) The maximisation of operations which are feasible by (one) locating candidate with a minimum of reconfigurable modules (high operation commonality, mutual use and low module number);
- (2) The division of the assembly system according to different locating candidates in separate modules with high throughput (low operation mutuality and high module number).



The arrows indicate the transfer from one module to another one

Figure V.27. Locating strategies

These philosophies correspond to the challenges addressed by the research cluster, in particular the question of flexible and modular systems versus high performance specific and dedicated systems. The schemes of both strategies are illustrated in Figure V.27. In strategy (1), a module gathers more operations, and the operations or locating candidates are mobile (movement flexibility) in order to realise all operations on the same locating candidate. Strategy (2) has more different modules with static locations and gathers less operations which allows the adaptation of the modules to the operations and requires no or less kinematic flexibility. In the following subsections, these two strategies are detailed.

V.4.1.1. Illustration of strategy 1

For the application of strategy (1), the precedence-location graph is taken as input. The information about precedence sequences and overlapping or separated locating candidate zones is used as follows: gather locating candidates as soon as possible in the assembly plan and maintain them as long as possible. The locating candidate gathering allows to visualise the operation sequences with all of their possible locating candidates as illustrated in the following figures.

An accumulation is possible from the first occurrence of a locating candidate as long as the sequence is not interrupted. The hypothesis is that a precedence sequence assembles a subassembly. Therefore, locating candidates occurring in the beginning of a precedence sequence can be used for assembly operations later on, even if they have not been identified explicitly as candidates. This because the locating candidate becomes part of a subassembly and is therefore, in theory, always available. The accessibility has nevertheless to be verified before validation. In a next step, for the application of the first strategy, the accumulation allows to identify the locating candidates which gather the most operations.

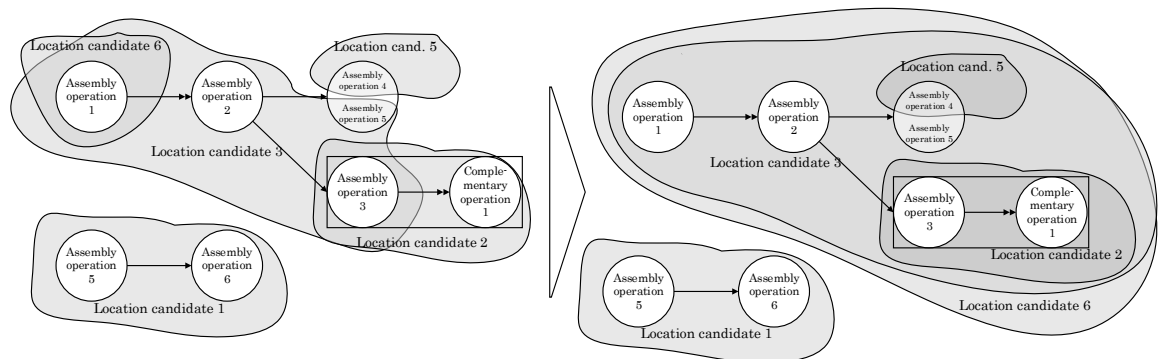


Figure V.28. Accumulation of locating candidates

Figure V.28 illustrates the accumulation. Candidate 6, which occurs in the beginning of the upper sequence is maintained up to the end. The area of candidate 3 has been extended. As locating candidate 1 in the lower sequence is separated (no precedence relations between the sequences), no change has been made. The locating candidates 2 and 5 occur at the end of their respective sequences. Thus no change has been made concerning these two. In the next step, the operations are listed with the accumulated locating candidates.

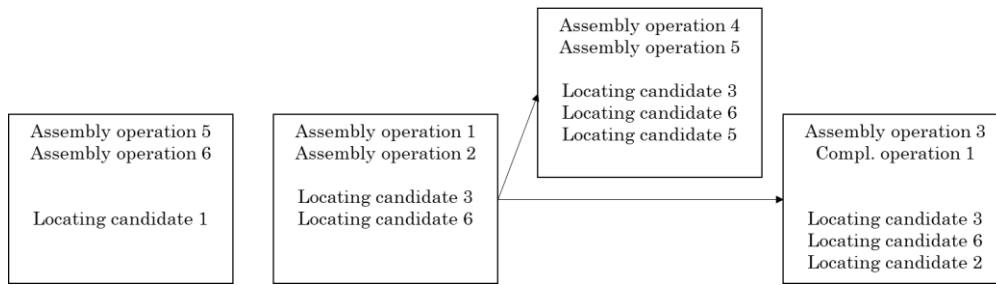


Figure V.29. Operations list with accumulated assembly candidates

It can be seen that the locating candidates 3 and 6 cover a big part of the operations. As they cover exactly the same, no preference between them can be expressed. Therefore, strategy 1 results in two possibilities for locating candidate sequences. Either candidate 1 and candidate 3, or candidate 1 and candidate 6.

V.4.1.2. Illustration of strategy 2

Here as well, the precedence-location graph is the methodology input. The information of precedence sequences and overlapping or separated locating candidate zones is used as follows: select different locating candidates as soon as possible and prefer the change of locating candidates when possible by avoiding accumulations or the reuse of locating candidates.

This selection method allows to visualise operation sequences with its optimum locating candidate and eases the differentiation point identification. However, the selection of locating candidates needs selection criteria when multiple choices are possible. Four different criteria can be applied for a selection:

- Choosing the configuration that brings together the most operations per locating candidates;
- Choosing the configuration that minimises operations with locating candidates which are not desirable (return of experiences);
- Complexity evaluation of locating candidates (estimation of their implementation complexity);
- Investment estimation to realise the component positioning with chosen locating candidates.

Alternatively, no criteria are applied and all solutions are generated to enlarge the solution space.

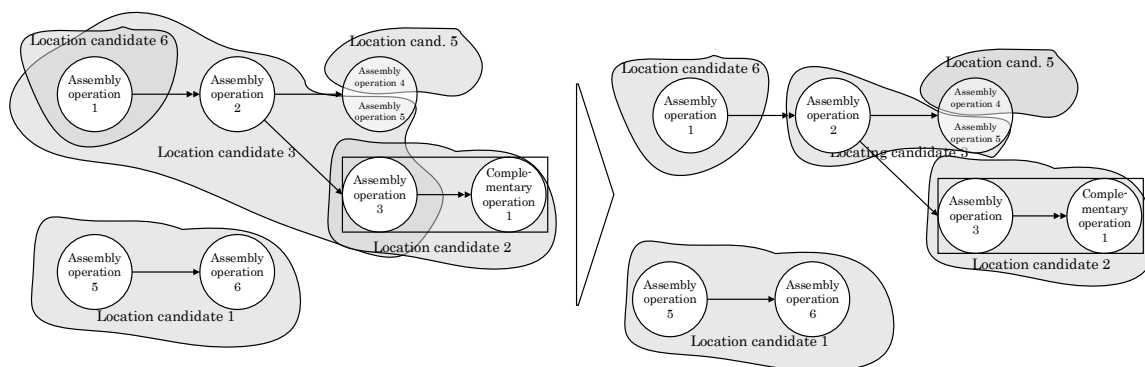


Figure V.30. Differentiation of locating candidates

Figure V.30 shows the differentiation. No selection is required since no multiple choices exist in the illustration. Attention has to be paid to the operations realised at the same time which needs in this case to use in parallel location candidate 5 and location candidate 3.

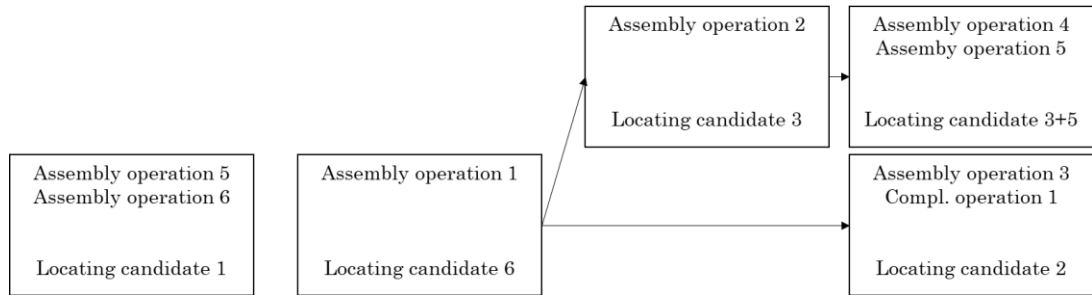


Figure V.31. Operations list with differentiated locating candidates

The obtained operations lists with differentiated locating candidates, the locating modules, are illustrated in Figure V.31. It can be seen that all locating candidates are distinct for a set of operations. No candidate is used more than one time and no accumulation is done. Locating candidate 1 is independent from the others. Assembly operation 1 is assigned to locating candidate six. A particularity occurs concerning the locating module of operation 4 and 5: as two different locating candidates are needed to realise these operations and the operations are realised in parallel, the two locating candidates have to be merged into a common locating with candidate 3 and 5.

Example V.6: Locating strategies for the ball pen example

The locating-precedence graph for the ball pen has been introduced in Figure V.26. The graph showing the accumulation locating candidates, according to strategy (1) is illustrated in Figure V.32. Locating candidate 5 has been discarded as it could not be extended due to accessibility issues. For the same reasons, locating candidate 2 could not be extended as well. The operation “(to) press-fit” has a more restrictive precedence constraint to enable unique location with component 2.

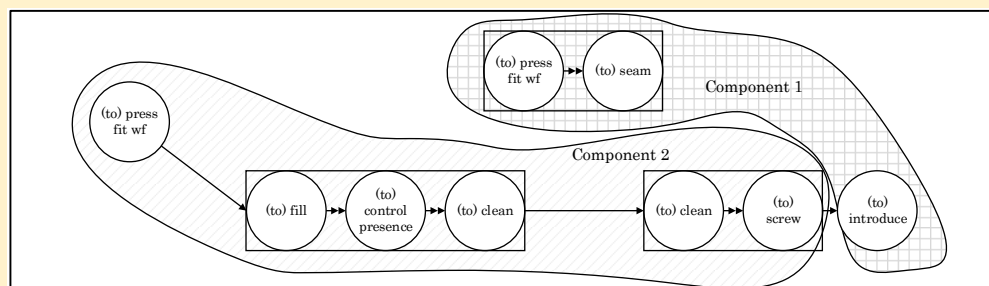


Figure V.32. Ball pen - accumulated locating candidates

In contrast, two possible solutions exist for strategy (2), illustrated in Figure V.33. Either the operation “(to) press fit” is realised with locating candidate 3 or with locating candidate 5. The next section shows how to determine the operation precedencies in this case.

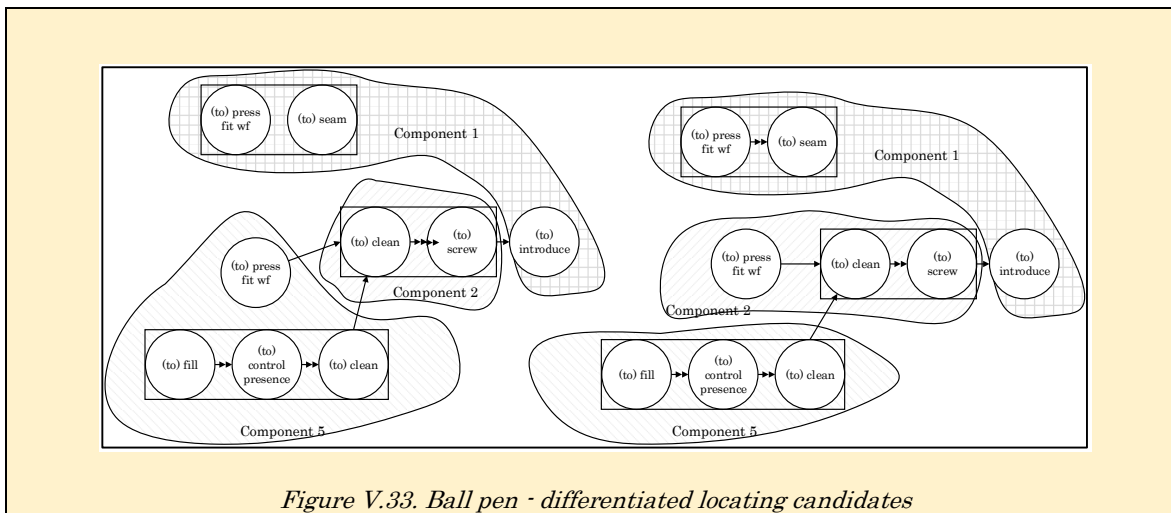


Figure V.33. Ball pen - differentiated locating candidates

V.4.2. Applying operation sequencing

In complex assemblies, it may happen that an independent locating candidate module exist which uses the same locating candidate as several modules embedded in a precedence sequence. In this case, the independent module should be mutualised with the embedded ones. The question is on which embedded one it should be integrated. Table V.2 furnishes an example of decision making criteria which can be used to answer this question.

Depending on the industrial application, the application of all criteria at the same time could be contradictory. Or, as the list is not supposed to be exhaustive, supplementary criteria could be needed. A case where gathering criteria were needed is presented in the Chapter VI.

Table V.2. Location gathering criteria

Gathering criteria (locating candidates)	Expected impact on assembly system
Gather with the ones having the same locating candidate	Minimise module number and redundant location candidates: System complexity decreases
Gather with the ones having operations of the same type	Minimise operation changes: System complexity decreases
Gather with the ones having operations with the same orientation	Minimise orientation changes: System complexity decreases Module complexity decreases

After the preliminary generation of location sequences (or one location sequence, depending on the chosen strategy and criteria), operations have to be sequenced as well. The sequencing of locating components gives a macroscopic sequence but in between each locating module, if there is more than one operation, the operations must be sequenced as well to determine the final assembly plan. Either criteria are applied for operation sequencing, or all possible sequences are generated to have an unlimited solution space. Concerning the criteria, Table V.3 gives an overlook.

Table V.3. Operation sequencing criteria

Sequencing criteria (operations)	Expected impact on assembly system
Insert operations according to their type	Minimise operation changes: System complexity decreases Module complexity decreases
Insert operations according to their orientations	Minimise operation orientation changes: System complexity decreases Module complexity decreases
Insert operations according to their value added to the assembly or risk	Minimise reject costs
Insert operations according to the size increase of the assembly	Minimise subassembly size: Needed workspace decreases Module complexity decreases
Insert operations according to the weight increase of the assembly	Minimise subassembly weight: Actuator requirements decreases System complexity decreases
Number of loose parts in the subassembly	Minimise the number of clamping: Module complexity decreases
Insert operations according to their reliability (less reliable at first)	Minimise reject costs
Insert operations to obtain a linear assembly flow	Minimise flow management complexity: System complexity decreases

Analogous to the gathering criteria, the list does not pretend to be exhaustive and may vary depending on application cases. And the application of all criteria at the same time is likely to give contradictory results. One should choose the most relevant ones and define priorities to avoid this.

Example V.7: Operation sequencing for a ball pen

This example is based on locating strategy (2) – differentiation – and uses the configuration defined on the left hand side of Figure V.33. The sequence of locating modules is 5 → 2 → 1.

The operations of locating module five are already defined through precedencies. It is (to) fill → (to) control presence → (to) clean. When it comes to locating module 2, two options are possible: insert the sequence of locating module 5 before, or in the middle of locating module 2. (see Figure V.34).

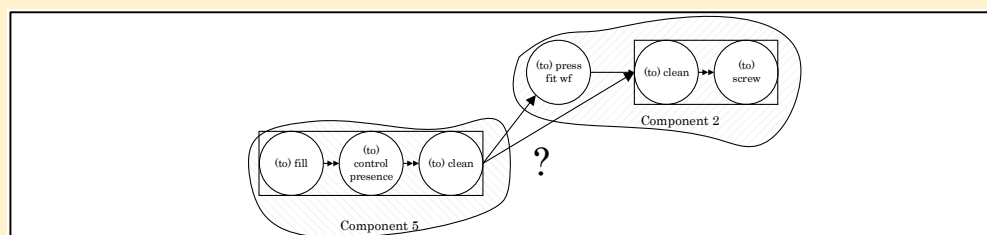


Figure V.34. Ball pen operation sequencing 1

Choosing the criterion of a linear assembly flow, it is decided to insert the operations of locating module 5 *before* the operations of location module 2. A similar question concerns the insertion of the independent operations of locating module 1. Here also, two possibilities exist, as illustrated in Figure V.35.

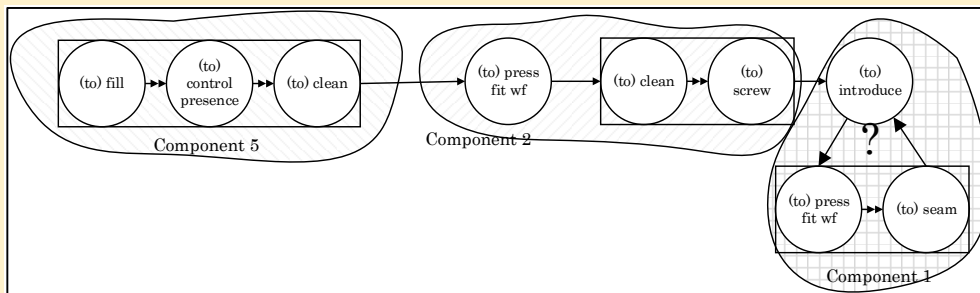


Figure V.35. Ball pen operation sequencing 2

To be consistent to the first sequencing problem, the linear assembly flow criterion is chosen again. Thus, the independent operations are added at the end. The final assembly sequence with locating modules is shown in Figure V.36. It is the preliminary assembly plan and has been determined by choosing locating strategy (2) and the sequencing criterion “linear assembly flow”. Without any preliminary decisions, 27 potential preliminary assembly plans can be generated for the ball pen.

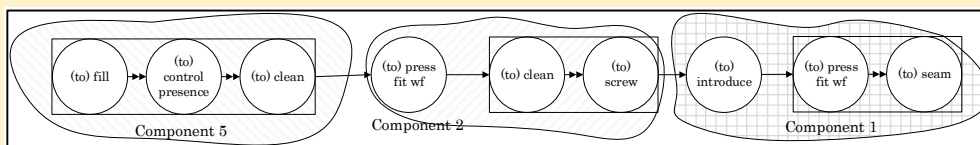


Figure V.36. One final preliminary assembly plan for the ball pen

V.4.3. Assembly sequence comparison

The literature review carried out that the mathematical reasoning of longest common sub-sequences (LCS) and shortest common super-sequences (SCS) has been used to compare different manufacturing lines with success, identifying idle machines and by-passes. The question is now, how to adapt the model of locating modules and assembly operation sequences to be adequate to the LCS-SCS reasoning. The aim is, that after the comparison different and common modules and sequences are identified and differences are quantified.

V.4.3.1. Compatibility and similarity issues

For assembly sequence comparison, one information needed: the similarity of locating candidates in the two examined products. To assure the compatibility of a locating module for a multi-product assembly, it has to be assured that the corresponding locating candidates have a corresponding shape and geometry. For this, the similarities have to be examined in a first step and a list of similar locating candidates has to be dressed. This analysis is for instance realised manually. It is recommended to set up gradually a file where this information is stored.

V.4.3.2. Applying LCS and SCS logic to assembly comparison

The reasoning of LCS-SCS has been examined in mathematics and computer sciences for a certain time now. Though, its applications to industrial problems is quite recent, as highlighted in the literature review. In a first step, the generic concept of LCS and SCS is reminded with the example of the two character sequences $seq_1 = \{FAAHFR\}$ and $seq_2 = \{ADHDFNR\}$. Their LCS and CSC are illustrated below:

F A A H F R	(seq ₁)	F A A H F R	(seq ₁)
A H F R	(LCS)	F A D A H D F N R	(SCS)
A D H D F N R	(seq ₂)	A D H D F N R	(seq ₂)

Transposed on a production system comparison problem, each letter stands for a unit (module, machine, work station, etc.). Same letters mean same units. The LCS gives thus an information, which units can be used mutually and the SCS gives an information about the unit sequence which is valid for all of the examined sequences. The comparison may be binary or for more than two sequences.

Beside the analysis of the LCS or SCS strings themselves, three indicators are introduced to have the characteristics of the comparison outcome at a glance:

- (1) LCS length compared to the length of the shortest initial sequence(s);
- (2) SCS length compared to the length of the longest initial sequence(s);
- (3) Number of characters in the LCS compared to the number of different characters used over all (Jaccard's similarity).

For the first indicator, it is analysed if it is equal to one or not. If it is equal to one, this means that one of the initial sequences is also the longest common sub-sequence. For the assembly system, it means that one product can be realised entirely on the LCS, and supplementary units are needed for the other units.

The second indicator is analysed as well if it is equal to one or not. If it is equal to one, it means that one of the longest sequences is also the longest common super-sequence. In terms of the assembly system this means that the production line of one product is capable to realise all products, however some units are not fully charged (idle machines).

Finally, the value of the third indicator evaluates the mutuality of the assembly units. If it is high, it means that the number of units used in the common part is close to the overall number of units used which indicates a high mutuality and low idle units. For low values, vice-versa.

V.4.3.3. Modelling locating module and operation sequences for SCS/LCS use

The generic principles of LCS/SCS and their analysis for assembly sequence comparison have been mentioned. Hereafter, a methodology is presented to transform the newly developed generic assembly plans containing locating module sequences and operation sequences to character strings which are the input for the analysis.

For this purpose, an analogy with biology is proposed: assembly sequences are compared with DNA and its base pairs (not to be mixed up with chromosomes and genetic algorithms). The assembly sequence, here the locating module sequence with assembly operation sequences, is the DNA of the assembly system. The assembly operations are its base pairs. Each operation itself, i.e. each base pair, is defined by the

three parameters locating module, operation, and operation orientation. Like the DNA is specific for each living being, the preliminary assembly plan is particular to the product. The analogy illustrated in Figure V.37.

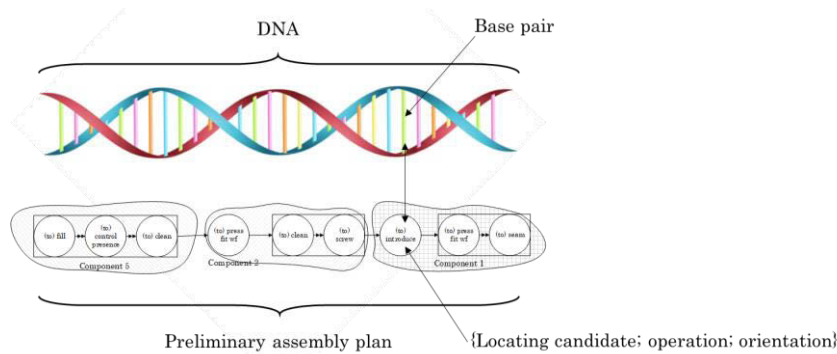


Figure V.37. Analogy DNA - preliminary assembly plan

As for DNA comparison base pairs are compared, for preliminary assembly plan comparison the triple information {locating candidate; operation; orientation} can be compared. It contains information on three different levels, which has a different impact on the assembly system.

- Locating candidate: assembly system structure level (same or different units)
- Assembly operation: assembly unit level (reconfigurable or mono-operational)
- Operation orientation: assembly operation level (flexible or rigid)

Therefore, by choosing to compare all of the information or only a part of it, one can determine the granularity of the comparison. In general, there are three options reaching from macro-comparison to micro-comparison:

- Option 1 (locating candidate only): The preliminary assembly plans are compared only in regard of their locating module sequences and similarity. This results in a macro view of the sequence similarity. Neither the number of operations nor their type or direction considered. This analysis could be suitable for the comparison of assembly systems with manual realisation of all operations or fully reconfigurable systems.
- Option 2 (locating candidate and operation): This analysis considers both locating candidate and their associated operations. Operation orientations are not considered. The result is a more detailed analysis of similarity than option 1. The application is the comparison of preliminary assembly plans in regard of locating module sequences, compatibility and operation sequences. It allows a vision on the system architecture level with its assembly units which may be work stations or assembly modules.
- Option 3 (locating candidate, operation, and orientation): It is the most detailed analysis comparing all the information. It is oriented towards a comparison for decisions concerning dedicated assembly systems (if the similarity is high enough).

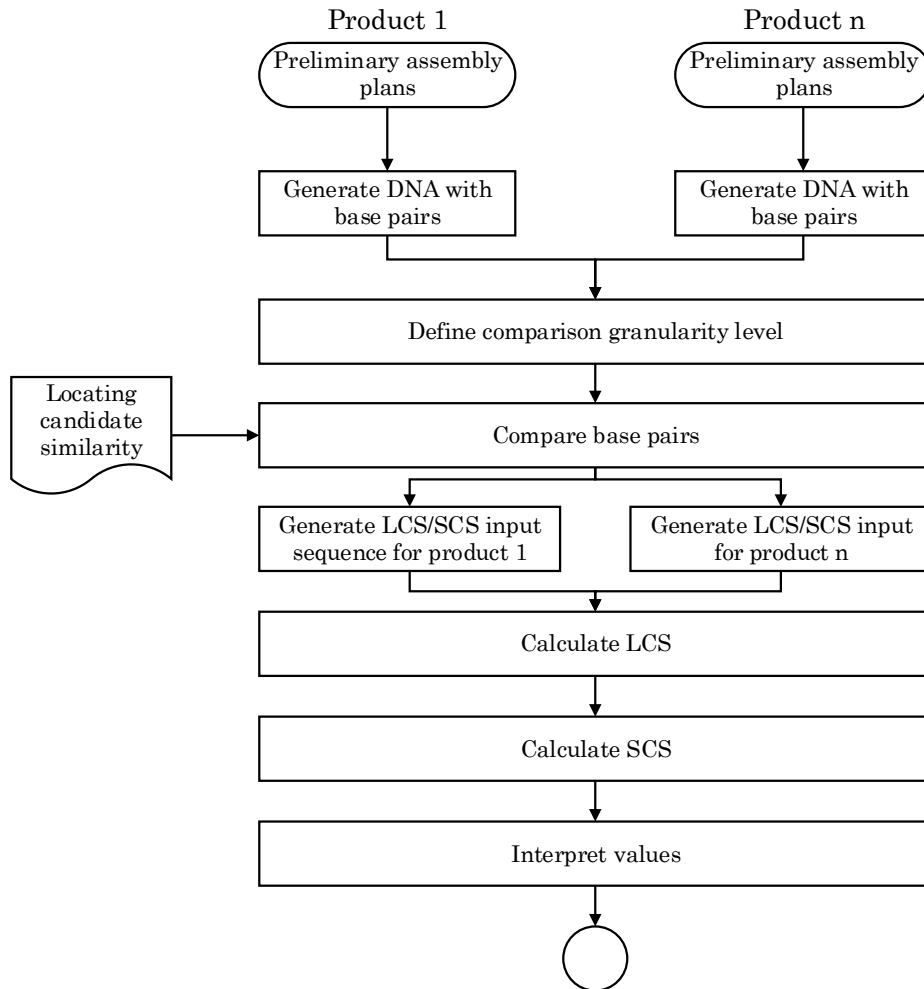


Figure V.38. Assembly sequence comparison method

The overall methodology using the DNA analogy is described in Figure V.38. The base pair definition, character sequence determination and calculations are introduced in the following section.

V.4.3.4. Character sequence determination and comparison

For the character sequence determination, the base pairs have to be defined. The preliminary assembly plan is translated into a sequence of base pairs, the DNA.

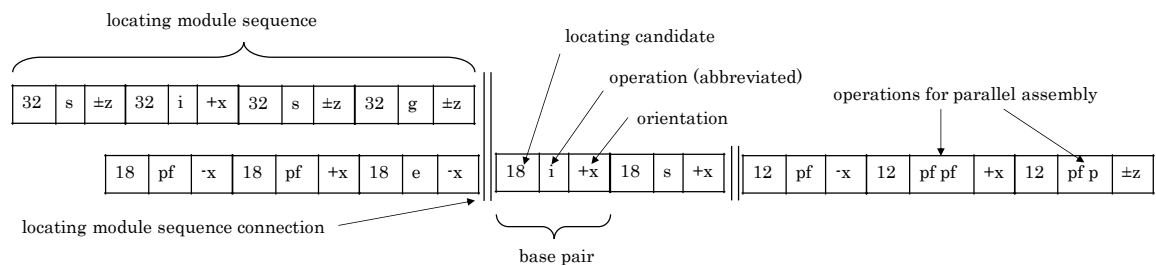


Figure V.39. Example of a preliminary assembly plan translated into DNA form

Figure V.39 shows a preliminary assembly plan translated to DNA. The base pairs contain the information of locating candidate, operation, and operation orientation for

each of the assembly steps. The preliminary assembly plans are based on locating module sequences. These are kept in the DNA representation and their interconnections are shown by cuts in the DNA sequence. This representation finally enables comparison of two or more preliminary assembly plans.

The comparison step is dedicated to generate the input sequences for LCS and SCS calculations. The input sequences are determined by comparing the base pairs in regard of the chosen options defined in the previous section. Concerning the locating candidates, the predefined information if locating candidate are similar has to be used. All the base pairs throughout the DNA are analysed. If two base pairs are identical in regard of the chosen criteria, the same character is assigned to them. If not, different characters are assigned. The flow chart for this process is illustrated in Figure V.40. It can be done for two or more products.

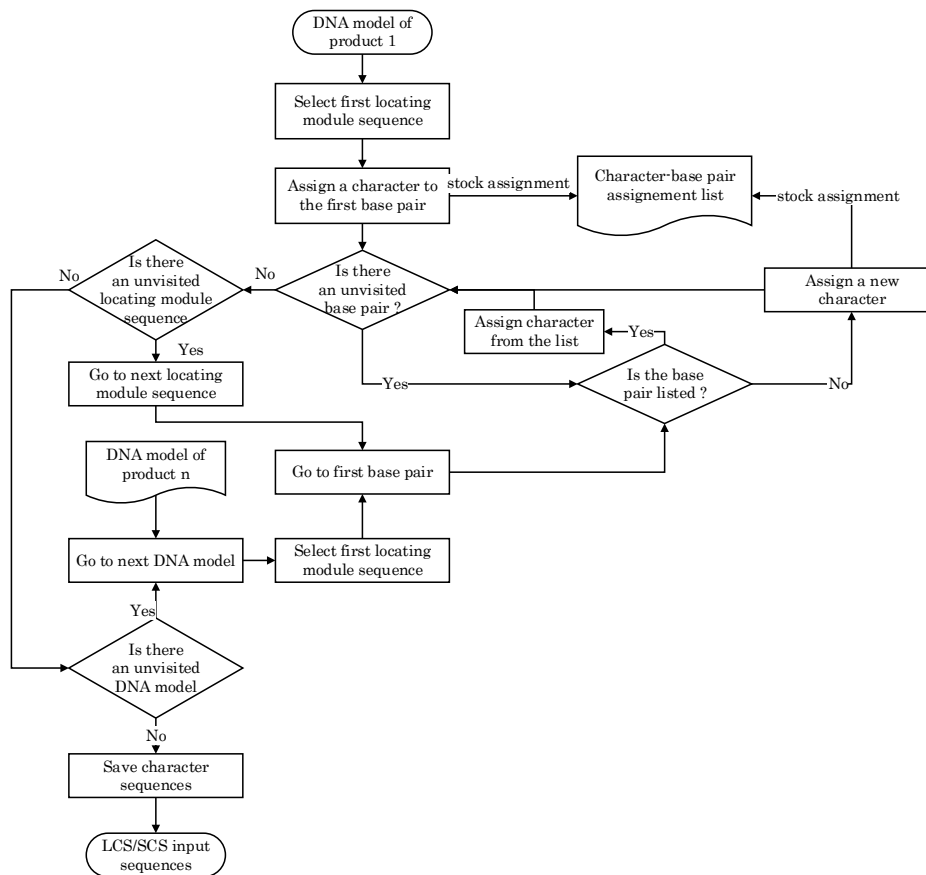


Figure V.40. Flow chart for the generation of LCS-SCS input sequences out of assembly DNA

The output is a character sequence for each DNA model. The character sequences may look like the ones used in the precedent section to illustrate LCS and SCS. As the preliminary assembly plans are based on locating module sequences, the analysis of LCS and SCS is based on it as well. In the flow chart, the analysis by sequence module is mentioned. Input sequences for LCS and SCS calculations are split into sequences by locating module. With the information on similar locating candidates, similar locating modules are known. The sequences of these similar locating modules are analysed with LCS and SCS. If there are sequences of a product which have no counterpart in other products, due to the lack of compatible locating candidates, these are not available for similarity comparison. An illustration is given in the example.

Example V.8: Comparison of ball and feather pen assembly sequences

For the ball pen, the preliminary assembly plan in Figure V.36 is taken as input. Its DNA representation is shown below. The information about orientations has been extracted from the assembly information template. It is implicit in the precedence-location graph.

5	f	-x	5	cp	y	5	c	±x	2	pf	wf	-x	2	c	±x	2	s	+x	1	i	+x	1	pf	wf	-x	1	se	-z
---	---	----	---	----	---	---	---	----	---	----	----	----	---	---	----	---	---	----	---	---	----	---	----	----	----	---	----	----

For the feather pen, the following sequence has been determined (see Appendix A):

1	f	-x	4	s	+x	4	se	+x	8	pf	wf	-x	8	s	in	+x	7	i	-x	7	pf	wf	set	+x	7	cl	set	+x
2	f	-x																										

The comparison of the locating candidates shows the following concordances (ball pen <> feather pen): 5 <> 1; 5 <> 2; 2 <> 8; 1 <> 7. Considering a comparison of locating candidate and operation, following the procedure described in the flow chart, the LCS/SCS input sequences are the following:

- Ball pen: {ABC}, {DEF}, {GHI}
- Feather pen: {A}, {A}, {JK}, {DL}, {GMN}

The sequences are gathered by locating modules. Analysis is done by locating candidate concordances. For the sequence {JK} of the ball pen no corresponding sequence exist for the feather pen.

The first comparison is therefore {ABC} versus {A}, {A}:

LCS= {A}, SCS= {ABC}. Indicator 1 = 100%, indicator 2 = 100%, indicator 3 = 50%.

The operation sequence ABC of the ball pen includes at the same time operation A of the feather pen. Thus, the feather pen assembly can be integrated to the ball pen assembly with two idle operations.

The second comparison is {DEF} versus {DL}:

LCS= {D} (length 1), SCS= {DLEF¹} (length 4). Indicator 1 = 1/2 = 50%, indicator 2 = 3/4 = 75%, indicator 3 = 1/3 = 33%.

The super sequence is composed of elements of both sequences. Only one element is in common, three elements are different. Poor possibility for mutual units.

The third comparison is {GHI} versus {GMN}:

LCS= {G} (length 1), SCS= {GHIMN} (length 5). Indicator 1 = 1/3 = 33%, indicator 2 = 3/5 = 60%, indicator 3 = 1/4 = 25%.

The super sequence is composed of elements of both sequences. Only one element is in common, three elements are different. Poor possibility for mutual units.

A recommendation for the production system could be: Mutualise the first assembly module. Then separate the flows.

¹ Only one SCS is displayed as all possible SCS have the same length (DLEF, DELF, DEFL). The same for the third comparison.

The poor commonality of the preliminary assembly plans reflects as well the poor similarity values of the two pen types.

Table V.4. S_1 and S_2 values for pen types

[%]	FSA 1	FSA 2	FSA 3	FSA 4	FSA 5
S_1	0	38	19	9	0
S_2	60	88	51	64	100

Both, product architecture and complexity similarity values indicate that the assembly system structure for the products will differ. In addition to that, mediocre assembly technology similarity values point at the fact that finding common assembly operations is difficult. This is confirmed by the fact, that some common elements have been found, however not enough to form similar sequences.

Table V.5. S_3 and S_4 values for pen types

[%]	FSA 1	FSA 2	FSA 3	FSA 4	FSA 5
S_3	50	50	50	none	0
S_4	0	none	none	0	0

Three possible application case for the LCS/SCS analysis exist. The first is the comparison of an existing assembly plan (of an existing product already in production) to a set of possible assembly plans for a new product in order to determine which of the assembly plans for the new product matches the best the one for the existing product. It is an analysis for the integration of a new product to an existing assembly line.

The second case is the comparison of two or more sets of assembly plans to each other. It determines which combination of assembly plans is the best one. The analysis considers the development of a new assembly line for a set of new products which are not yet in production.

The third case is the parallel analysis of assembly plans for multiple products when determining the preliminary assembly plans. It is an optimisation approach to generate one optimal solution for multiple products. It is in contrast to the two other approaches where first the solution space is generated and explored afterwards.

Ideally, the analysis of the similarity values S_1 - S_4 gives an idea about the preliminary assembly plan similarity and correlates with the commonality of the assembly plans. The problem concerning the application of similarity values to the preliminary assembly plan comparison is that the logic of functional subassemblies used for product analysis has been replaced by a logic of locating modules. The two concepts are orthogonal to each other as illustrated by Figure V.41. One locating candidate can include several FSA and vice-versa.

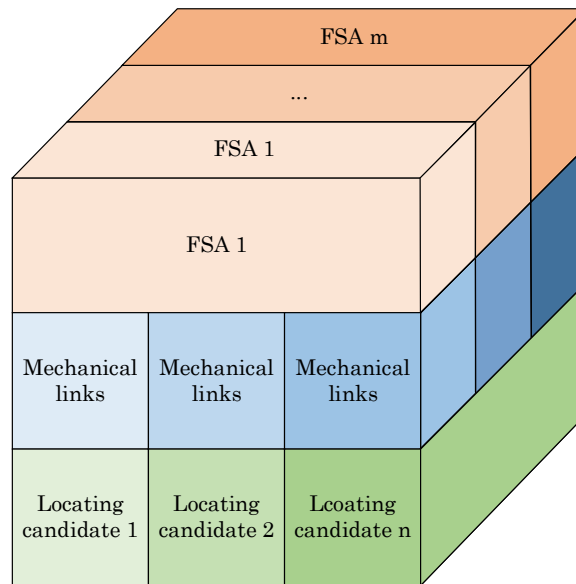


Figure V.41. View of locating candidate versus functional subassembly

In general, it can be stated that the locating modules which have perfect or high similarity scores include the same FSA, and locating modules with different FSA have less commonality. Evaluating the two different kinds of similarity values, it can be stated that low similarity values for S_1 and S_2 has an impact on two aspects: it increases the possibility to have differing FSA in the locating modules. And it increases the risk that the sequences in the locating modules differ due to structural differences in the product architecture. Concerning S_3 and S_4 , low similarity scores increase the risk to have different assembly operations in the locating modules, i.e. differing characters in the LCS/SCS input sequences. A similarity analysis on the products used for the industrial case study confirmed these global statements.

V.5. Conclusions of the chapter

In this chapter, models and approaches have been introduced to accomplish the step from the product modelling part to assembly system design. The end point of the work is the generation and comparison of preliminary assembly plans which contain information about locating module sequences and allocated assembly and complementary operations. The approach has been tested on three complex mechanical products of our industrial partner (up to 50 components and 20 different technical functions).

The generation of precedence constraints with a logical expression approach has been introduced. The advantage of this approach is its flexibility for the input of different precedence constraint types (accessibility, operations or others) which makes it adaptable to various industrial applications. Basing the precedence constraints on the enriched DFC model has two advantages: At first, the enriched DFC model allows the initial generation of the component matrix \mathbf{C} in which the precedence constraints are added. And second, it allows a partial identification of precedence constraints with patterns using assembly information connected with the recognition of subgraph structures. The use of four patterns has been validated through manual applications, but the realisation of an implementation is needed to really support the process with automatic deductions. The enriched DFC being already integrated to the software

prototype the recognition of intrinsic precedence constraints could be done automatically as well but needs further investigation on the application of pattern matching. All the other precedence constraints, in particular accessibility and operational constraints, have to be identified and added manually because no geometrical and material information is contained in the enriched DFC model. Manual constraint input has always the risk that the operator doing the task defines more constraints than necessary and adds constraints which are more linked to personal preferences than technical requirements. Furthermore, the repeatability of manual data input depends strongly on the formation, strictness and precisions of the operating employees. To overcome this potential risk, the feasibility of linking the enriched DFC model to CAD models to add geometry and material information could be examined, even if this link seems difficult to realise.

Next, the identification of locating candidates has newly been introduced. Locating candidates are a key element for the generation of assembly plans as the new approach is oriented towards the sequencing and the comparison of locating modules. A graph theory approach (sinks and sources) has been adapted to the problematic of candidate identification. It allows to generate numerous possible locating variations without considering personal preferences which can influence the choices done by an industrial expert. The proposed candidates also could encourage new solutions which have not been considered before. Through this approach extended with a rule set, coupled with the enriched DFC, locating candidates can be identified automatically. The candidate identification has been linked to the assembly information template. For instance, the candidates have been identified manually, but once an implementation is realised, a list of locating candidates with their belonging mechanical links may be generated. However, the verification of the locating candidates which are all theoretically possible, needs always to be done manually as the product model based approach may propose impossible candidates (for example “ink” in the pen examples). These need to be discarded. Also, there is a risk that a candidate can be ignored because it fulfils not the predefined criteria, a case which is theoretically possible but which has not occurred during the case studies. Nevertheless, the preselection offers a smaller number of candidates to examine as a complete verification of all products and the enriched DFC based method ensures their integration into the product structure.

When it comes to the combination of locating candidates with precedence constraints, the component based precedence information, which contains implicitly information about the mechanical link, has to be converted to represent explicitly precedence information of mechanical links. Both, precedence constraints and locating candidates are combined to a new product model, the precedence-location graph. This graph is the departure point for the preliminary assembly sequence generation. By displaying locating possibilities, it enables the application of sequencing strategies which are based on locating decisions. Either all possible assembly sequences can be generated or, by application of refinement criteria concerning locating module sequences and operation sequences, a more restricted set of solutions may be generated. The viability and the reliability of the precedence-locating graph depends strongly on the information input which has been realised beforehand. Therefore, a particular attention should be paid to the definition of precedence constraints and locating candidates as well on the preselection of locating candidates. The information treatment and the representation generation of the precedence-locating graphs have not been implemented yet. The work has been done manually with Excel (data treatment) and Visio (graphical representation). As always, manual manipulation of an important amount of

information (for example, the locating candidate tables can easily have sizes superior to 20x60, i.e. 1200 cells) is sensitive to input errors. Upcoming work should include the automation of information treatment.

Beside the generation of assembly plans, their comparison is of high importance for decision making concerning the structure of the assembly systems and the product mix to send on the assembly lines. A new reasoning based on locating module sequences has been introduced to face product variety and propose a locating oriented view of assembly. Based on this locating oriented view, a new comparison approach has been introduced, using the theory of LCS and SCS for sequence comparison. The first point revealed is that the proposed model of locating-precedence graphs is fully usable and adaptable to be processed with LCS/SCS approaches. The needed transformation is done by a DNA analogy. The developed comparison method allows to compare sequences by locating candidates and points at commonalities as well as it indicates differences. The entire approach has been worked through manually. An implementation has not begun yet. Although the generation of the DNA model, the comparison and LCS/SCS input sequence generation, and the LCS/SCS calculation are supposed to be implementable, a proof has to be given.

Concerning the application of the overall approach, the generation of precedence constraints have been applied to three complex mechanical products of the industrial partner. The locating candidate identification has been applied to four different products, and the preliminary assembly plan generation and comparison has been tested on three products. The methods have been theoretically validated through these industrial case studies. However, a practical evaluation, i.e. simulation validation or implementation of a system developed with this reasoning is pending.

Furthermore, the complete approach from precedence constraints to preliminary assembly plans is oriented to the technical solutions. It generates solution spaces based on a set of generation criteria. No decision making logic has been integrated yet, though possible connection points exists. Thus, it needs to be coupled with evaluation and decision making approaches. Also the solution generation is for instance quite linear, that means for a set of input data, a set of possible solutions is proposed without doing a statement about the fitness of the proposed solutions. To improve this, optimisation approaches could be coupled, in particular for assembly plan generation and comparison.

Last, concerning the assembly sequence generation for products, the new locating candidate based approach has to be applied to further industrial case studies to make it more viable. The impact of strategy choices and sequencing constraints on the solution space has to be examined more in detail. A confrontation of the new approach with a classical assembly sequencing approach across a same industrial case study would be beneficial to highlight the change of viewpoint through the new approach. For this, the literature references identified in the first part of the literature review, in particular [Rampersad 1994], [Stadzisz and Henrioud 1995; 1996], and [De Lit and Delchambre 2003] could be used as starting point.

Chapter VI. Industrial case study

This chapter presents the application on an industrial case study of the models, methods and tools presented in the previous three chapters: three products out of the product portfolio of our industrial partner. The application on the products, the used files, and resulting data are detailed as much as possible due to confidentiality. Product and process analysis as well as the generation of preliminary assembly plans and their comparison are addressed.

During this research work, several industrial case studies have been carried out in cooperation with our industrial partner. Throughout these case studies, the developed methods, tools and applications could be verified in terms of: efficiency, applicability and reliability. In this chapter, excerpts of the case studies are given, focusing on three of the eleven examined products. For reasons of confidentiality, the data has been anonymised and the products cannot be displayed. For the comparison, a functional framework for products has been defined with the industrial partner, which contains 22 elementary technical functions.

The first two ones, here called “Product 1” and “Product 2”, are sophisticated mechanical products allowing height and length adjustment with comfort components. The third one, called “Product 3”, is a basic mechanical product which permits only a height adjustment without any comfort components. The former ones are composed of about 50-65 components. Product 1 satisfies 20 and product 2 satisfies 21 of the 22 elementary technical functions. The latter one consists of 22 components fulfilling 14 elementary technical functions.

Two reasons guided the choice to show these particular three products: First, product 3 differs a lot from product 1 and product 2, which are considered to be quite similar. The choice of these products allows therefore to illustrate how the product models and applications represent similarity and differences. Second, the choice of product 1 and product 2 has been guided by the fact that the partner company has been faced with a decision problem during the integration of product 1 to production. It has been decided to put it on the production line of product 2, a choice which lead to some practical problems. This case illustrates, that even though the products seem similar at a first glance, the consequences of this empirical similarity does not imply similarity on the production level.

Chapter VII. General conclusion and perspectives

This chapter is dedicated to the global conclusion of the presented research work and its perspectives. The conclusions show off the limits of the presented applications. The perspectives, at the same time academic and industrial application oriented, are gathered by the research areas which are concerned.

The aim of this research is to propose a contribution to the co-design of product, process and production system in the context of reconfigurable assembly process. It has been carried out as applied research in strong cooperation with the industrial partner in order to assure that the proposed solutions meet industrial requirements and are applicable in the industrial context.

VII.1. Conclusion

To remind, the global research question which has been defined in the beginning of this document as frame for the research work is

How to analyse, measure and increase the agility of a production system?

In this field of research, the specific research topic has been defined by the following scientific issue:

How to design a reconfigurable production system considering product families and their assembly by addressing co-evolution aspects?

Out of this key questions, a set of three research objectives has been defined. The structure of this conclusion follows these three aims.

VII.1.1. Aim 1: Enable the analysis of products and product families characterised by product variety

To respond to the research questions of aim 1, two new product representations have been introduced: the enriched DFC which represents the product assembly with its mechanical links, its assembly technologies and link attributes used to realise the mechanical links, and the functional subassemblies which indicate the components participating to the realisation of a technical function of the product.

Based on the enriched DFC, the PHARE model has been introduced, which displays the architecture of products in terms of their hybrid physical and functional structure. Concerning that the referential of technical functions is the same for all examined

products, the PHARE model enables the comparison of a product variety where component-based approaches fail due to differing component number and type.

With these two product models, the requirements as defined for aim 1 are satisfied: they enable the analysis and comparison of a product variety in terms of product architecture and assembly technologies.

Limitations of the application are given by the technical function referential which has to be common for all of the examined products. It does not support the comparison of completely different products, regarding the function they perform, which may have the same assembly technologies. Also, the proposed assembly technology knowledge is not exhaustive, as it is oriented towards the industrial use cases, and can be completed.

VII.1.2. Aim 2: Enable the identification or improvement of product families

To answer the questions of research aim2, four new similarity indices have been defined. Two are based on the PHARE representation and evaluate the functional and architectural design and complexity similarity. The two others are defined on the level of the enriched DFC and evaluate assembly technology similarity in the functional subassemblies as well as the similarity of technologies used to assemble them. For the technology similarity, two calculation methods have been proposed: a basic method using binary evaluation (zero similarity or perfect similarity) and an extended method taking into account the similarity of operations and technologies for the global similarity calculation. The four indices correspond to a set of application:

- The product portfolio design analysis, by examining and comparing all similarity values for a given product portfolio;
- The gathering of products into product families, by analysing either the design similarity values S_1 and S_2 , or all four similarity values;
- The improvement of product design similarity based on the improvement of the four indices;
- The deduction of production system paradigms for a combination of functional subassemblies by analysing the four similarity scores.

All these applications have been applied on industrial case studies and validated theoretically. This means that the analysis results and the proposed modifications and conclusions have been judged by industrial experts, but an implementation has not been realised due to time constraints.

The similarity index approach is heavily dependent on its industrial application. This means that the similarity indices, based on the two new product models, are a tool for product variety analysis, but this tool has a local perimeter. The values with their belonging deductions which have presented are linked to the products and the production processes of the industrial partner company. When applying to new, different cases, a calibration phase is necessary, to define value domains, thresholds and their interpretation. Similarity value meanings with their belonging thresholds which are valid for one industrial company and application are not meant to define globally valid statements. However, the methodology and its applications are globally applicable.

VII.1.3. Aim 3: Enable the preliminary generation of alternative assembly plans

To answer the challenges linked to aim 3, a new view of a production system is proposed: instead of having modules by assembly steps, a view focusing of the components used for locating is proposed. This focus allows to define locating modules, i.e. modules which gather operations around the component whose positioning in the module allows them. The identification of these locating modules permits the application of different strategies for the system architecture and generating multi-product assembly lines by compatible locating components. Reconfigurability is enhanced by having multiple possible operations around one assembly location.

To generate the according preliminary assembly plans, three different aspects have been addressed:

- The identification of precedence constraints, which is supported by a partial automatic identification by patterns in the enriched DFC representation;
- The identification of functional subassemblies relevant for assembly by contracting the PHARE models;
- The identification of locating candidates, i.e. components which are used as base parts for an assembly.

Based on these information, a new product view, the precedence-locating graph is generated, which is used to generate sets of feasible preliminary assembly plans. The solution space can be restrained by applying sequencing constraints. Finally, to enable the comparison of preliminary assembly plans to determine multi-product assembly lines, a DNA inspired approach has been proposed which enables the generation of character strings representing assembly sequences for comparison with LCS/SCS methods. This comparison helps to determine common and different parts in the assembly sequences.

The proposed approach enables the generation and comparison of preliminary assembly plans, which has been tested throughout an application on three complex mechanical products of the industrial partner. The new reasoning by locating candidates and modules lead to the development of a new kind of assembly module and assembly process in the industrial partner company, which is supposed to meet their reconfigurability needs.

The approach itself relies strongly on the definition of the basic models (enriched DFC and PHARE) which means that the generation of preliminary assembly plans is sensitive to the consistency of the product modelling. Furthermore, during the identification of locating candidates and precedence constraints, their (partial) input and validation through an operator is used. Different operator having a different vision/view of the assembly might introduce also inconsistencies and operators may add unessential constraints due to their personal preferences. These factors can impact the generated solutions as well as the reliability of the comparison. As all these applications rely on enriched DFC and PHARE, their limit of use is defined by the referential of technical functions, as mentioned in the previous sections.

VII.2. Perspectives and future works

The presented research work, including product, process, and production system, covers multiple research aspects. Perspectives for further development exist in each of them. A glance of the overall research work, its models and methods, as well as the covered research aspects are illustrated in Figure VII.1 which reminds the structure of the research work as presented in the introduction. The global research work and its applications cover three research areas which are indicated by colours in the figure:

- The area of products and assemblies modelling (brown);
- The area of product variety management, including product family generation and product design improvement (green);
- The area of product-process integration for sequence generation and assembly system architecture design (yellow).

For each of the models and approaches which have been presented in this work, their limits are emphasised in the following and perspectives for further work are shown off.

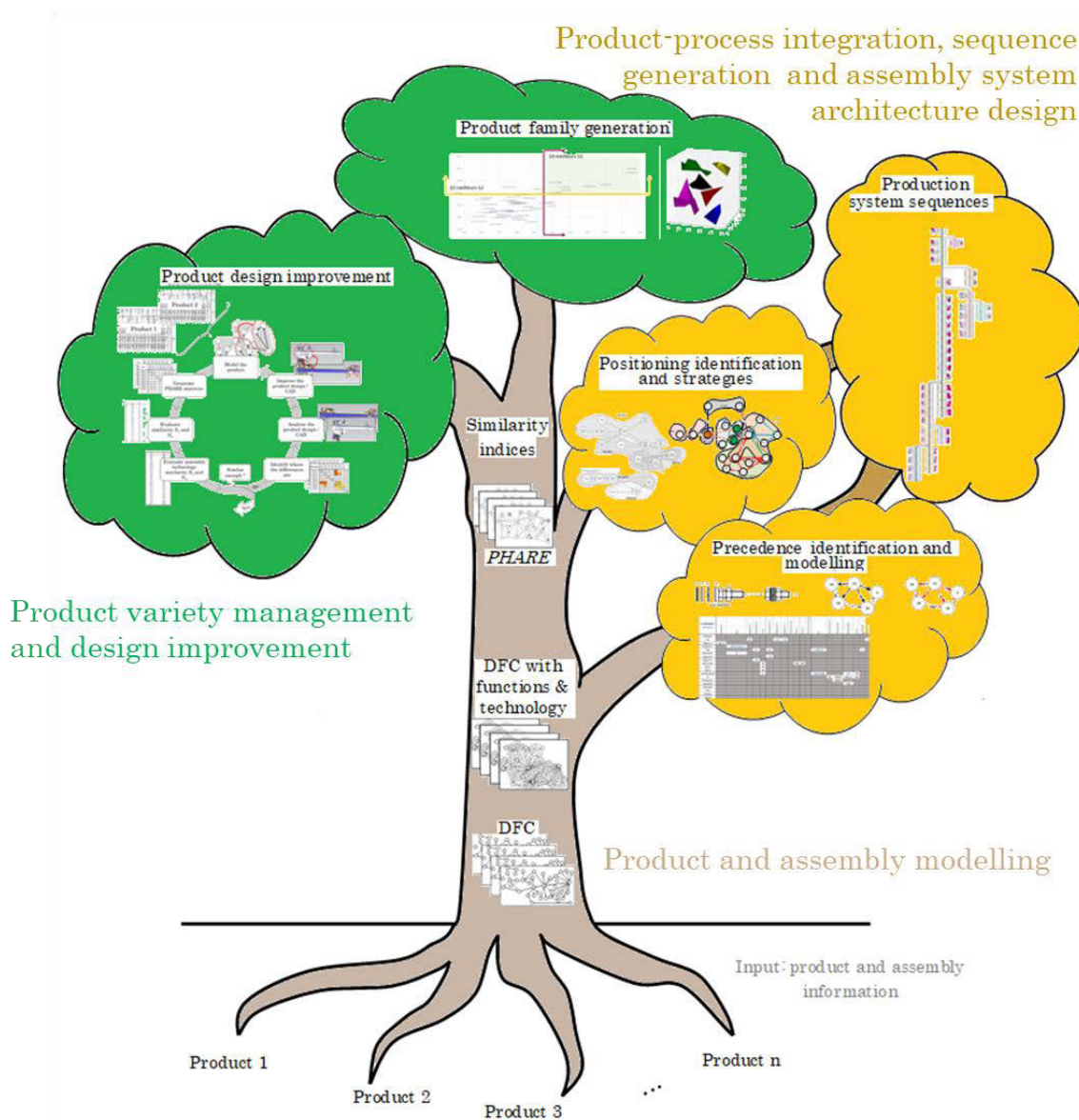


Figure VII.1. Research work and concerned research areas

The **PHARE approach** is limited to a technical function referential. For the industrial case studies, it has been applied to a large product variety, proving its applicability to product variety analysis. Though, the products are all belonging to a same category. When comparing product varieties belonging to different product categories, the technical referential has necessarily to become more generic. This abstraction leads to a loss of technical meaning for the technical functions and therefore also a loss of the technical meaning of functional subassemblies in the PHARE approach. For example, quite precise technical functions could be found for the pen types used in the examples. These all belong to the category of writing tools. It is obvious that the technical function framework will fail to compare pen types with a completely different product category, e.g. water kettles. But it will also be rare to find a company producing both in a same production plant. However, considering a company producing office tools, it could be challenging to compare staplers, perforators and adhesive tape supports within one technical function referential. **Further work on this issue should examine the limits of the technical function referential applications.**

Concerning the **enriched DFC**, in the proposed approach it covers information about mechanical links, relative component locating, eliminated degrees of freedom, used assembly technologies, and link attributes. **Further information could be added at this stage which can support decision making during the assembly sequence generation**, reflecting the proposed criteria: for example, the classification of mechanical links as furnished by assembly drawings, the size and weight of the components, or the value added by a mechanical link for the assembly.

Finally, the **assembly analysis and comparison** based on the two models has been applied successfully. It has been revealed that the meaning and generation of the indices S_1 and S_2 is not easily comprehensible for untrained users without in depth explications. This can be an obstacle for the quick deployment of these indices. Concerning the calculation of S_1 and S_2 , all FSA and all relations are considered equally. **A refinement can be done by weighting relations or by weighting some functional subassemblies which are considered more important than the others.** Finally, as mentioned in the previous chapters, even if the approach is software supported, a human intervention for information input is always necessary. A lot of attention has to be paid to the consistency of the information input, especially if several different operators do it independently. An inconsistency of the data models can falsify all applications of the PHARE approach.

All along the PHARE approach and its applications, **assembly process knowledge** is needed and used. In this research work, a taxonomy has been proposed to frame this knowledge. For each of its categories, elements (operations, parameter types, ...) have been defined. All this information has been connected by defining the links between the elements. However, it has not been formalised in a specific expression (e.g. first order logic). **So further work can be the translation of rules and constraints belonging to the elements of the taxonomy categories into a CSP solver to enable their implementation.** Also, the proposed list is not exhaustive, as it focuses on the main technologies, operations and parameters which have been used for the industrial case study applications. As some knowledge is specific to companies and their processes, it may necessary to change the classifications in behind the taxonomy categories. This means that for new, different applications it has to be checked that all needed information is available. During further case studies, to others than the products used for this research work, the sensitiveness of the classifications should be verified.

For **product variety management**, product family generation and product design similarity improvement, several applications have been presented. All these are based on the similarity indices S_1 to S_4 . Three approaches (supervised learning, unsupervised learning and statistical analysis) have been proposed for family generation and variety analysis and management. They show the possible use cases. Concerning the supervised learning approaches, their overall applicability has been shown, but precise input-output pairs need still to be determined in cooperation with the industrial partner. Also, the possible deductions have to be verified through supplementary case studies. **Concerning the clustering approach, additional criteria than the indices S_1 to S_4 could be added.** By this, other criteria than design and assembly technology may be considered. Also, further work is needed to determine if the four indices have to be considered equally as it is done for instance, or if adding preferences enables a better and more distinct family identification.

Finally, concerning the **product design similarity improvement**, the proposed methodology points at differences in the product design and assembly technology choices, and proposes improvement possibilities (a solution space). But no decision making support is furnished, as for instance the decision which changes to make is left to the operator. To close this gap, **for each loop proposing changes, a DFA analysis can be coupled. By this way, the aspects of cost and assembly efforts are integrated to the improvement loop and furnish a decision making help. Further development on the iterative process should include this.**

The third aspect of the research work concerns product-process integration for the generation of preliminary assembly plans. It starts with the identification of **precedence constraints**. Patterns have been defined which enable the partial automatic recognition of precedencies in the enriched DFC. These four patterns are generally applicable. However, it may be that the list is not exhaustive or that additional patterns can be found specific to industrial applications. Therefore, **additional work can be carried out on the pattern definition.** Concerning the additional precedencies which have been identified manually, the risk of omissions or over-constraining is present. Concerning the information input, an integration of precedence definition to the software prototype could support the operator. It could be imagined that precedencies are linked to the definition stage of the enriched DFC.

Concerning the **locating candidate identification**, the identification of functional subassemblies relevant for assembly and the gathering of assembly information in the assembly information templates is done manually in different files for instance. An implementation of these functionalities could support the data input and treatment and shorten processing times. The method as developed during the research work results in a set of possible locating candidates. Analogous to the product similarity improvement, no statement is given, which of them are the most performing ones and, if a locating strategy is chosen, which one is the best in terms of return of investment, throughput, plant implementation or others. **This means that the results of the locating candidate identification need to be submitted to an evaluation stage to determine which one to choose.** The same can be said about the generation and comparison of preliminary assembly plans.

The presented approach, by the **comparison of preliminary assembly plans** with application of LCS and SCS methods, allows to identify which parts of the assembly

sequences are common, similar or different. This information helps to define the overall architecture of the assembly system. However, when it comes to the detailed implementation, the decision making, which technology to choose for each module and how to build the modules, no further decision support is given. **Further work should integrate information to the approach which supports decision making.** It is about examining the possibility of a joint application of optimisation methods during the generation phases in order to generate one optimised result instead of a solution space. **An Operations Research oriented approach using linear integer programming, and having in the constraint and objective function definition criteria as cost or throughput to evaluate investment and performances can be combined with the assembly sequence generation approach.** The idea is to evaluate sequences during their generation in an iterative way. Or the approach can be oriented towards the **coupling of the solution generation with simulation approaches and tools**, so that decision making can be based on the simulation of different scenarios. As no algorithm has been developed yet, the computing time for the solution generation is uncertain. Also, even if the first link between the similarity indices and the assembly sequence similarity has been done during this work, a more detailed analysis is needed to determine clearly the deductions which can be taken out of the similarity values and where the limits of this analysis are situated. **It would be interesting to determine which one or which combination of the four indices is pertinent for the sequence similarity** and if an index score improvement is not only efficient for design similarity improvement but also system architecture similarity improvement.

The conclusion and perspectives show off that the developed approach has multiple docking points where it can be completed or extended with existing methods. Also, although the presented methods, tools and models have been tested thoroughly with industrial case studies, there is space left for refinement. Therefore, the validated elements of this research work provide several different starting points for further research work covering aspects from product design over process integration to production system architecture design.

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Picture references

Preface

Figure 2. Industrial challenges

- Logo Toyota: <http://marque-voiture.com/le-logo-de-toyota/>
(accessed 15.03.2020)
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(accessed 15.03.2020)
- Logo Volvo: <https://www.imin30.com/logo/logo-volvo-1462>
(accessed 15.03.2020)
- Logo Bosch: <https://www.cpe.fr/wp-content/uploads/2017/09/2017-logo-Bosch-1024x294.jpg>
(accessed 15.03.2020)
- Logo Valeo: <https://phileum.com/wp-content/uploads/2016/01/valeo-logo.png>
(accessed 15.03.2020)
- Logo Schaeffler: <https://cdn.worldvectorlogo.com/logos/schaeffler-logo-1.svg>
(accessed 15.03.2020)
- Logo Faurecia: <https://www.faurecia.com/sites/groupe/files/pages/logo.png>
(accessed 15.03.2020)
- Logo thyssenkrupp: <https://www.brandsoftheworld.com/logo/thyssenkrupp-2>
(accessed 15.03.2020)

Figure 3. Dedicated production vs multi-product line

- Logo General Motors: <https://www.car-logos.org/wp-content/uploads/2011/09/gm.png>
(accessed 22.03.2020)
- Logo Opel: <https://automarken-logos.com/opel-logo/>
(accessed 22.03.2020)
- Production system: https://www.festo-didactic.com/ov3/media/customers/1100/do438_11c_ov.jpg
(accessed 22.03.2020)

Chapter III

Figure 0.1. A set of several pen types

- Above: <https://www.officeworks.com.au/shop/officeworks/p/artline-smoove-ballpoint-pen-blue-pai82103>
(accessed 20.02.2020)
- Middle: <https://www.montblanc.com/fr-fr/collection/writing-instruments/meisterstueck/115384-meisterstueck-gold-coated-149-fountain-pen.html>
(accessed 20.02.2020)
- Below: <https://www.deprismedia.com/promotional-items/pens-writing-accessoires/plastic-pens/metmaxx-kugelschreiber-lightmywrite-blue.html>
(accessed 20.02.2020)

Chapter VI

Figure V.38. Analogy DNA - preliminary assembly plan

- DNA helix: <https://pngimage.net/dna-em-png-4/>
(accessed 27.03.2020)

Appendix A. Data models

A.1. Data structure of DFC and PHARE

The generic data structure of DFC, product, technical function and PHARE is illustrated in Figure A.1. The basic DFC uses information of components and mechanical links. Exactly two components form a mechanical link, where one component is the positioned one and the other the positioning one.

As described, a component is allocated to at least one technical function. In the opposite direction, a technical function can have components allocated, i.e. the technical function is realised and a functional subassembly is formed, or not. The combination of basic DFC with technical functions gives all information needed for the modelling of DFC with FSA.

Finally, the PHARE representation uses information about the technical functions which are related to each other. To sum up, for the generation of the presented models, information about components, mechanical assemblies and technical functions are needed. These are attached to one product. The models are specific for each product, which implies that a representation per product is necessary.

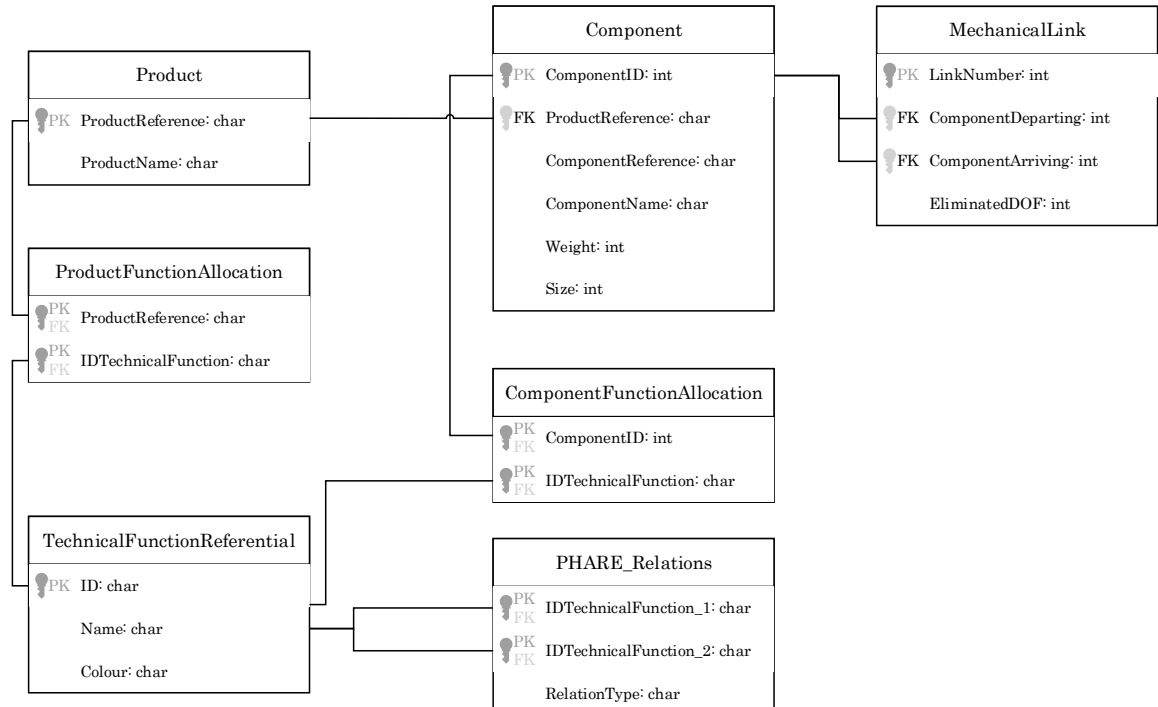


Figure A.1. Data structure of DFC and PHARE

A.2. Data structure of assembly knowledge

The data structure of assembly information is presented in Figure A.2. Component and mechanical link definitions are the same as in Figure A.1. The two representations are complementary. The focus is put on the actual topic and shows how the product model is connected to process information.

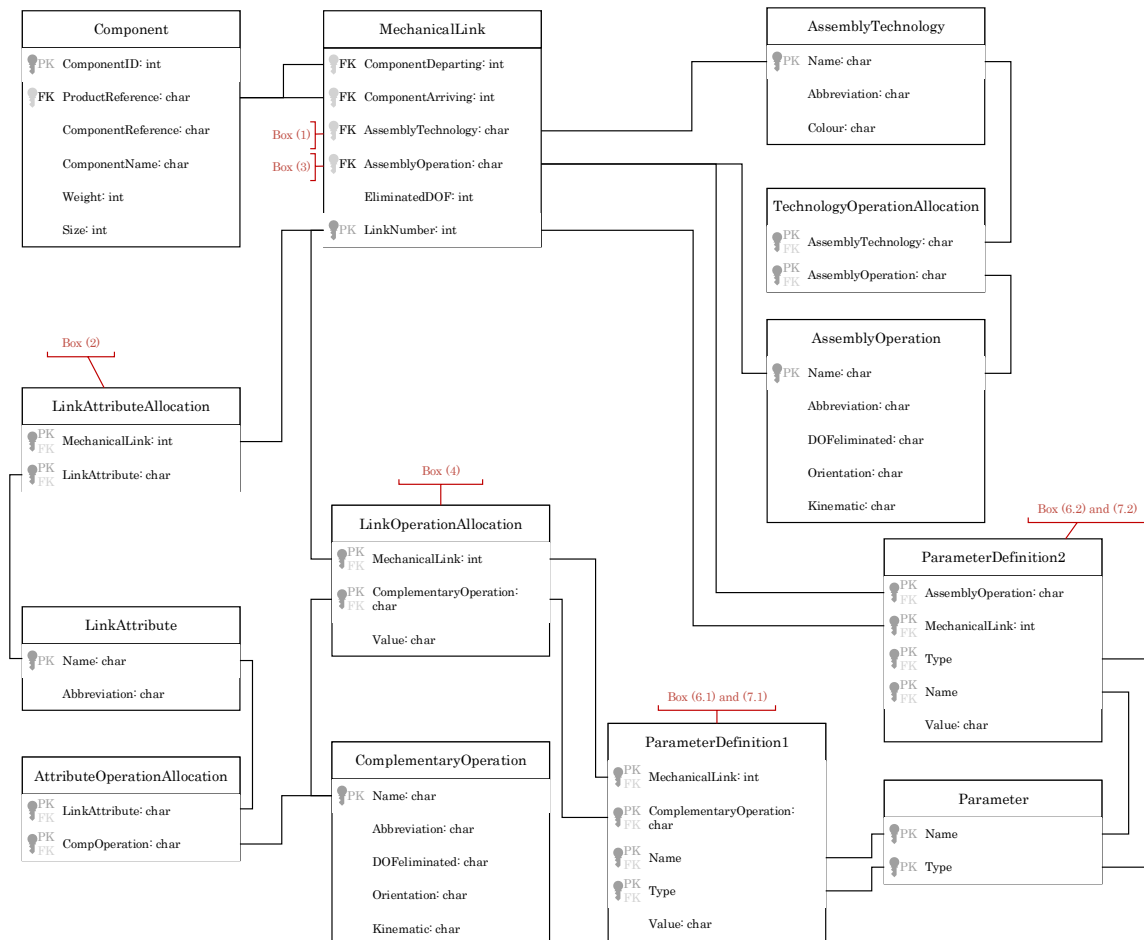


Figure A.2. Data structure of DFC and assembly information

All classifications and relations relative to the assembly technology data are available in Appendix B. To shape the new structure and classifications, one may state that an assembly process can be subdivided into several elements, all illustrated in Figure A.2. Assembly technology is linked to each mechanical link representing the choice of an assembly solution to realise the link. An assembly operation is attached to each mechanical link as well and belongs to a domain of assembly technologies. Depending on the operations, clamping may be necessary. The operations themselves are defined by a set of operation parameters (discriminant or operational) which are particular for each mechanical link.

The same is done for link attributes and complementary operations. One should note that more than one link attribute and complementary operation can be allocated to a mechanical link.

A.3. Data model for locating candidates

The following figure illustrates the data structure for locating candidates. It is integrated to the data model for assembly information which has been presented previously. Unneeded tables of the original data model are not displayed to enhance readability.

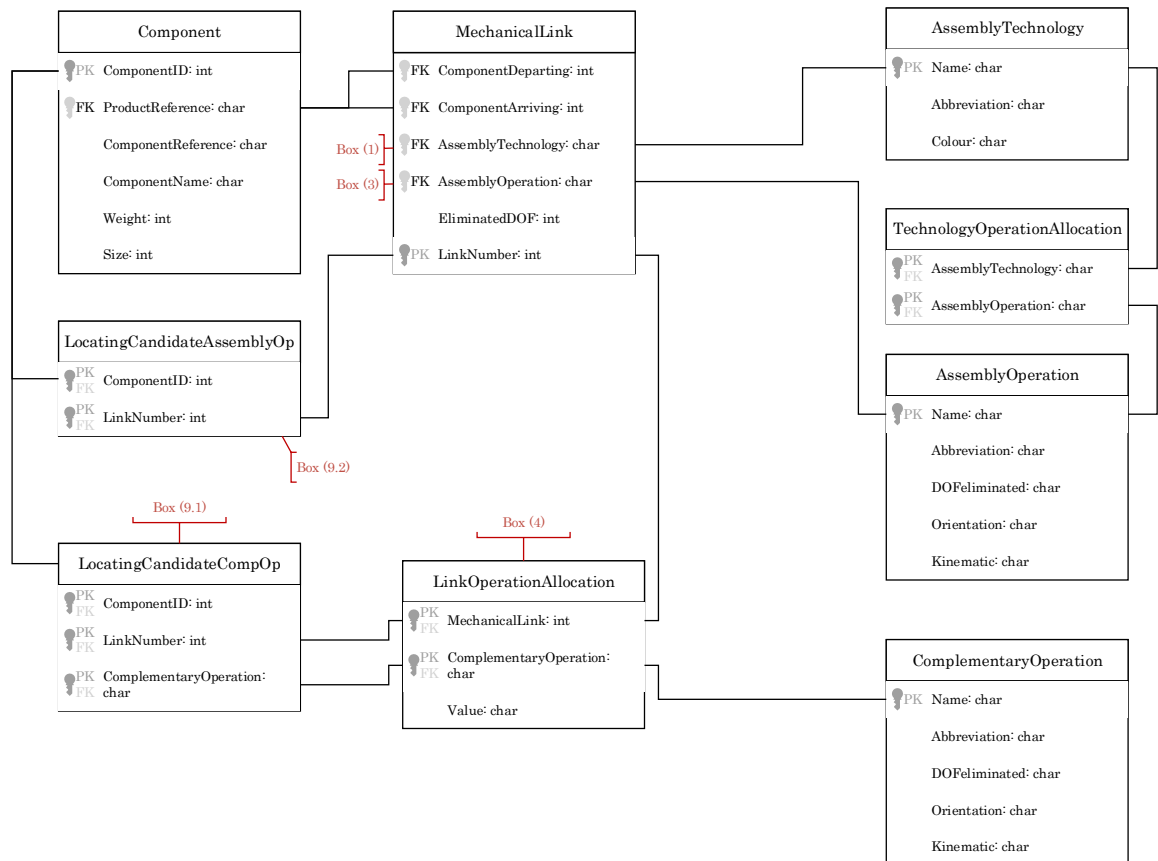


Figure A.3. Data structure for locating candidates

Appendix B. Assembly technology knowledge

B.1. Classifications

This classification can also be found in Chapter III.

Classification of assembly technologies:

{placing-charging (PC); filling (F); press-fitting and plaiting (PP); bolted assembly and screwing (BA); plastic deformation-seaming-folding (PS); riveting (R), welding-brazing (W), adhesive bonding (AB), clipping (C), marking¹ (M)}

Classification of link attributes:

{control (c); greasing (g); marking² (m); thermal treatment (t); cleaning (cl); straightening (st); coding (co); calibrating (ca); running in (r); seaming (s)}

Classification of assembly operations:

{(to) set; (to) introduce; (to) interlink; (to) hang up; (to) fill; (to) press fit with force; (to) press fit without force; (to) nail; (to) screw; (to) seam; (to) mould; (to) engrave; (to) mark; (to) clip; (to) gas weld; (to) arc weld; (to) plasma weld; (to) laser weld; (to) weld by electron beam; (to) weld by electric arc; (to) ultrasound weld; (to) friction weld; (to) braze; (to) glue; (to) rivet}

Classification of complementary operations:

{(to) mark; (to) measure forces; (to) measure torque; (to) measure power; (to) measure stiffness; (to) to measure distance; (to) measure concentricity; (to) measure swing; (to) measure velocity; (to) measure cone; (to) measure angle; (to) measure noise; (to) control coding; (to) heat; (to) cool; (to) clean; (to) run in; (to) straighten; (to) read code; (to) write code; (to) calibrate; (to) seam}

Assembly Operation Parameters:

{component presence; pressure; number-weight; force; position; torque; angle³; distance; noise; velocity; time; voltage; acceleration⁴}

Discriminant Parameters:

{force; pressure; volume-width; torque; frequency; number-weight; precision; angular position; lateral position; temperature; power; noise level; security}

¹ component graving

² marking a link

³ number of spins and final position (e.g. 540° = 1,5 spins)

⁴ in acoustics: vibration modes

B.2. Relations between assembly technology and assembly operations

placing-charging:	{(to) set; (to) introduce; (to) interlink; (to) hang up}
filling:	{(to) fill}
press-fitting and plaiting:	{(to) press fit with force; (to) press fit without force; (to) nail}
bolted assembly and screwing:	{(to) screw; (to) interlink; (to) set; (to) introduce}
plastic deformation-seaming-folding:	{(to) seam; (to) mould}
riveting:	{(to) rivet; (to) interlink; (to) set; (to) introduce}
welding-brazing:	{(to) gas weld; (to) arc weld; (to) plasma weld; (to) laser weld; (to) weld by electronic beam; (to) ultrasound weld; (to) friction weld; (to) braze}
adhesive bonding:	{(to) glue}
clipping:	{(to) clip}

B.3. Relations between link attributes and complementary operations

control:	{(to) measure force; (to) measure torque; (to) measure friction; (to) measure power; (to) measure distance; (to) measure stiffness; (to) measure concentricity; (to) measure swing; (to) measure cone; (to) measure velocity; (to) measure angle; (to) measure noise; (to) control coding (elv + label)}
greasing:	{(to) grease}
marking:	{(to) engrave; (to) mark}
thermal treatment:	{(to) cool; (to) heat}
cleaning:	{(to) clean}
straightening:	{(to) straighten}
coding:	{(to) read code; (to) write code}
calibrating:	{(to) calibrate}
running in:	{(to) run in}
seaming:	{(to) seam}

B.4. Eliminated degrees of freedom

B.4.1. Assembly technologies

placing-charging:	{1; 2; 3; 4; 6} degrees of freedom
filling:	{6} degrees of freedom
press-fitting and plaiting:	{4; 5; 6} degrees of freedom
bolted assembly and screwing:	{1; 2; 4; 5; 6} degrees of freedom
plastic deformation-seaming-folding:	{0; 6} degrees of freedom
riveting:	{1; 2; 4; 5; 6} degrees of freedom
welding-brazing:	{6} degrees of freedom
adhesive bonding:	{6} degrees of freedom
clipping:	{4; 5; 6} degrees of freedom

B.4.2. Link Attributes

control:	{0} degrees of freedom
greasing:	{0} degrees of freedom
marking:	{0; 6} degrees of freedom
thermal treatment:	{0} degrees of freedom
cleaning:	{0} degrees of freedom
straightening:	{0} degrees of freedom
coding:	{0} degrees of freedom
calibrating:	{0} degrees of freedom
running in:	{0} degrees of freedom
seaming:	{6} degrees of freedom

B.4.3. Assembly Operations

(to) set:	{1; 2} degrees of freedom
(to) introduce:	{3} degrees of freedom
(to) interlink:	{4; 5} degrees of freedom
(to) hang up:	{6} degrees of freedom
(to) clip:	{4; 5; 6} degrees of freedom
(to) fill:	{6} degrees of freedom
(to) press fit with force:	{6} degrees of freedom
(to) press fit without force:	{4; 5} degrees of freedom
(to) nail:	{6} degrees of freedom

(to) screw:	{6} degrees of freedom
(to) seam:	{5; 6} degrees of freedom
(to) mould:	{0} degrees of freedom
(to) rivet:	{5} degrees of freedom
(to) engrave:	{6} degrees of freedom
(to) gas weld:	{6} degrees of freedom
(to) arc weld:	{6} degrees of freedom
(to) plasma weld:	{6} degrees of freedom
(to) laser weld:	{6} degrees of freedom
(to) weld by electronic beam:	{6} degrees of freedom
(to) ultrasound weld:	{6} degrees of freedom
(to) friction weld:	{6} degrees of freedom
(to) braze:	{6} degrees of freedom
(to) glue:	{6} degrees of freedom

B.4.4. Complementary operations

(to) grease:	{0} degrees of freedom
(to) mark:	{0} degrees of freedom
(to) measure force:	{0} degrees of freedom
(to) measure torque:	{0} degrees of freedom
(to) measure friction:	{0} degrees of freedom
(to) measure power:	{0} degrees of freedom
(to) measure distance:	{0} degrees of freedom
(to) measure swing:	{0} degrees of freedom
(to) measure stiffness:	{0} degrees of freedom
(to) measure concentricity:	{0} degrees of freedom
(to) measure cone:	{0} degrees of freedom
(to) measure velocity:	{0} degrees of freedom
(to) measure noise:	{0} degrees of freedom
(to) control coding:	{0} degrees of freedom
(to) cool:	{0} degrees of freedom
(to) heat:	{0} degrees of freedom
(to) clean:	{0} degrees of freedom
(to) read code:	{0} degrees of freedom
(to) write code:	{0} degrees of freedom

(to) run in:	{0} degrees of freedom
(to) calibrate:	{0} degrees of freedom
(to) seam:	{6} degrees of freedom

B.5. Relation between operations and discriminating parameters

(to) set:	{number-weight; volume-width; none}
(to) introduce:	{number-weight; volume-width; none}
(to) interlink:	{number-weight; volume-width; none}
(to) hang up:	{number-weight; volume-width; none}
(to) clip:	{force; lateral position; precision; none}
(to) fill:	{volume-width; pressure}
(to) press fit with force:	{force; lateral position; precision}
(to) press fit without force:	{lateral position; precision}
(to) nail:	{force; lateral position}
(to) screw:	{torque; angular position; precision}
(to) seam:	{force; precision}
(to) mould:	{force; lateral position}
(to) engrave:	{volume-width; noise}
(to) gas weld:	{voltage; security}
(to) arc weld:	{voltage; security}
(to) plasma weld:	{voltage; security}
(to) laser weld:	{voltage; security}
(to) weld by electronic beam:	{voltage; security}
(to) ultrasound weld:	{voltage; security}
(to) friction weld:	{pressure; security}
(to) braze:	{voltage et security}
(to) glue:	{temperature et security}
(to) mark:	{volume-width; lateral position}
(to) grease:	{number-weight}
(to) measure force:	{volume-width; number-weight; precision}
(to) measure torque:	{volume-width; number-weight; precision}
(to) measure friction:	{volume-width; number-weight; precision}
(to) measure power:	{volume-width; number-weight; voltage; noise}
(to) measure distance:	{volume-width; number-weight; precision}

(to) measure stiffness:	{volume-width; number-weight; precision; force}
(to) measure swing:	{volume-width; number-weight; precision}
(to) measure cone:	{volume-width; number-weight; precision}
(to) measure velocity:	{volume-width; number-weight; precision}
(to) measure noise:	{noise; distance}
(to) control coding:	{volume-width; number-weight; precision}
(to) rivet:	{force; lateral position; precision}
(to) cool:	{temperature; time}
(to) heat:	{temperature; time}
(to) clean:	{volume-width; number-weight}
(to) read code:	{none}
(to) write code:	{none}
(to) run in:	{angular position; lateral position; velocity}
(to) calibrate:	{volume-width; number-weight; precision; lateral position; angular position}
(to) seam:	{force; precision; lateral position}

B.6. Relation between operations and operation parameters

(to) set:	{component presence}
(to) introduce:	{component presence}
(to) interlink:	{component presence}
(to) hang up:	{component presence}
(to) clip:	{component presence}
(to) fill:	{pressure; number-weight}
(to) press fit with force:	{force; position; distance; velocity; none}
(to) press fit without force:	{force; position; distance; velocity; none}
(to) nail:	{force; position}
(to) screw:	{position; torque; angle; velocity; force; none}
(to) seam:	{force; position}
(to) mould:	{velocity; pressure; temperature}
(to) engrave:	{none}
(to) gas weld:	{number-weight (of gas)}
(to) arc weld:	{voltage; tension; distance; velocity (wire)}
(to) plasma weld:	{voltage; tension; distance; velocity (wire)}
(to) laser weld:	{voltage; velocity (forward speed)}

(to) weld by electronic beam:	{frequency; tension; voltage}
(to) ultrasound weld:	{frequency; voltage}
(to) friction weld:	{velocity; pressure}
(to) braze:	{voltage; position; tension}
(to) glue:	{velocity; time}
(to) grease:	{number-weight; distance}
(to) mark:	{distance; position; none}
(to) measure force:	{force; position; velocity}
(to) measure torque:	{torque; angle; velocity}
(to) measure friction:	{force; position; velocity}
(to) measure power:	{tension; acceleration; voltage}
(to) measure distance:	{position; distance}
(to) measure stiffness:	{force; position; velocity}
(to) measure swing:	{position; angle}
(to) measure cone:	{position; angle}
(to) measure velocity:	{position; velocity}
(to) measure noise:	{bruit}
(to) control coding:	{position; component presence}
(to) rivet:	{force; position}
(to) cool:	{temperature; time}
(to) heat:	{temperature; time}
(to) clean:	{time; number-weight}
(to) read code:	{none}
(to) write code:	{none}
(to) run in:	{velocity; position}
(to) calibrate:	{velocity; angle; position; force; torque}
(to) seam:	{force; position}

B.7. Relation between operations and kinematics

(to) set:	{Linear}
(to) introduce:	{Linear}
(to) interlink:	{Linear}
(to) hang up:	{Linear; Complex}
(to) clip:	{Linear}

(to) fill:	{Linear; Complex}
(to) press fit with force:	{Linear}
(to) press fit without force:	{Linear}
(to) nail:	{Linear}
(to) screw:	{Linear}
(to) seam:	{Linear; Rotational}
(to) mould:	{Linear; Complex}
(to) engrave:	{Linear; Complex}
(to) arc weld:	{Linear; Complex}
(to) plasma weld:	{Linear; Complex}
(to) laser weld:	{Linear; Complex}
(to) weld by electronic beam:	{Linear; Complex}
(to) ultrasound weld:	{Linear; Complex}
(to) friction weld:	{Linear; Complex}
(to) braze:	{Linear; Complex}
(to) glue:	{Linear; Complex}
(to) grease:	{Linear; Complex; Rotational}
(to) mark:	{Linear}
(to) measure force:	{Linear}
(to) measure torque:	{Rotational}
(to) measure friction:	{Linear; Rotational}
(to) measure power:	{Linear}
(to) measure distance:	{Linear}
(to) measure swing:	{Linear}
(to) measure stiffness:	{Linear}
(to) measure concentricity:	{Rotational}
(to) measure cone:	{Linear}
(to) measure velocity:	{Linear; Rotational}
(to) measure Noise:	{Linear}
(to) control coding:	{Linear}
(to) rivet:	{Linear}
(to) seam:	{Linear; Rotational}

Appendix C. Feather pen product models

C.1. Product illustration

The feather pen example is also inspired by [Bourjault 1984]. Two modifications have been made: Ink has been added and the clip on the cap is not considered. The parts of the feather pen are illustrated in Figure C.1.

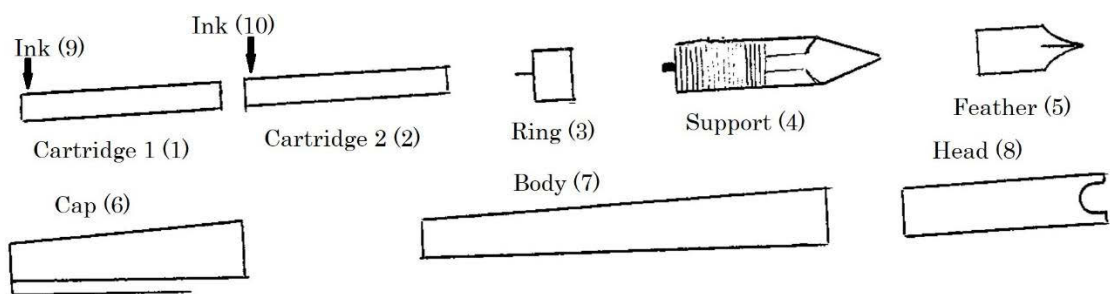


Figure C.1. Feather pen [Bourjault 1984]

C.2. Datum Flow Chain

Based on the product model and Bourjault's liaison graph, the DFC model is generated as illustrated in Figure C.2.

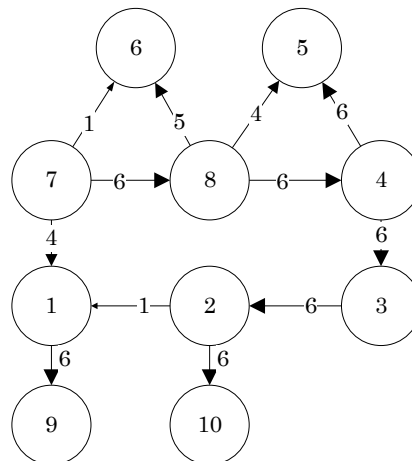


Figure C.2. Feather pen Datum Flow chain

The following assumptions are done:

- Ink is filled into the cartridges and the ink for each cartridge is considered as separate component;
- The base part for positioning propagation is the body (7), consistent the ball pen example;

- The head is positioned into the body;
- The cap is maintained by the head, the body limits only the course of the head;
- Cartridge 2 is inserted to the ring;
- Cartridge 1 is freely put into the body and its lateral movement is limited by cartridge 1 as well;
- The feather is fixed on the support and inserted into the head;
- The support is screwed into the head;
- The ring is screwed on the support.

All these assumptions explain the directions of the arc and the degrees of freedom eliminated.

C.3. Functional subassembly and assembly technology definition

The technical functions as defined for the comparison of different pen types are the following:

- | | |
|---------------------------------|-------------------|
| ▪ F1: Contain ink | FSA1: {1;2;9;10} |
| ▪ F2: Prevent ink from drying | FSA2: {3;4;6;7;8} |
| ▪ F3: Enable ergonomic handling | FSA3: {4;7;8} |
| ▪ F4: Ensure contact with paper | FSA4: {5} |
| ▪ F5: Erase writing | FSA5: {} |

According to this definition, the functional subassemblies are added to the DFC in Figure C.3.

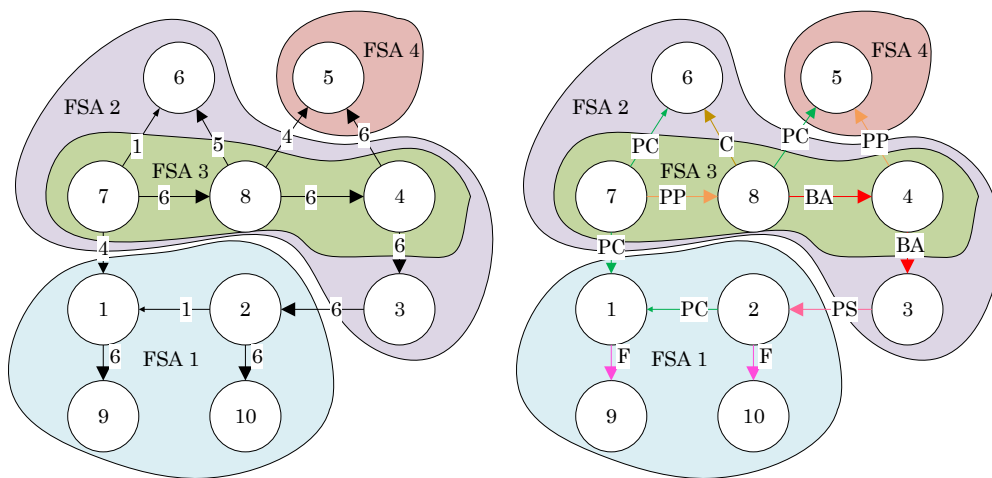


Figure C.3. DFC with FSA and DFC with assembly technologies for the feather pen

The assigned assembly technologies are:

- placing-charging (PC); colour green
- press-fitting and plaiting (PP); colour orange
- bolted assembly and screwing (BA); colour red
- filling (F); colour pink
- clipping (C); colour dark yellow
- plastic deformation-seaming (PS); colour salmon

C.4. PHARE representation

According to the PHARE generation rules, the DFC with FSA can be transformed into the following PHARE representation:

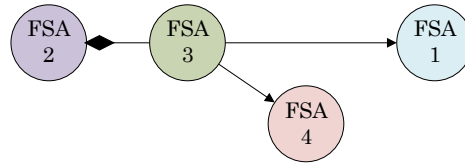


Figure C.4. Feather pen PHARE representation

C.5. Precedence constraints

Table C.1. Precedence constraint table for the feather pen

	1	2	3	4	5	6	7	8	9	10
1									x7	
2	1									x4
3		$>(x2 \wedge x4), x3$								
4			x2		x1					
5										
6										
7	$>x7, x8$					$>x6$		$>(x5 \wedge x8), x6$		
8				$>(x1 \wedge x3), x5$	$>(x1 \wedge x3), x5$	$>x6$				
9										
10										

All precedence constraints for the feather pen are indicated in the table above.

C.6. Locating candidates and precedence-location graph

Table C.2. Consolidated locating candidates for the feather pen

	1-9	2-10	2-1	3-2	4-3	8-4	4-5	8-5	8-6	7-6	7-1	7-8
1	1											
2		1	1									
3			1	1	1							
4			1	1	1		1					
5							1					
6									1			
7			1	1					1	1	1	1
8			1	1		1	1	1				

Out of the consolidated locating candidates, in combination with the precedence constraints, the precedence-locating graph can be generated. The minimum number of locating candidates is chosen for the graph. The locating candidates are {1;2;4;7;8}. The according precedence-location graph is illustrated in Figure C.5.

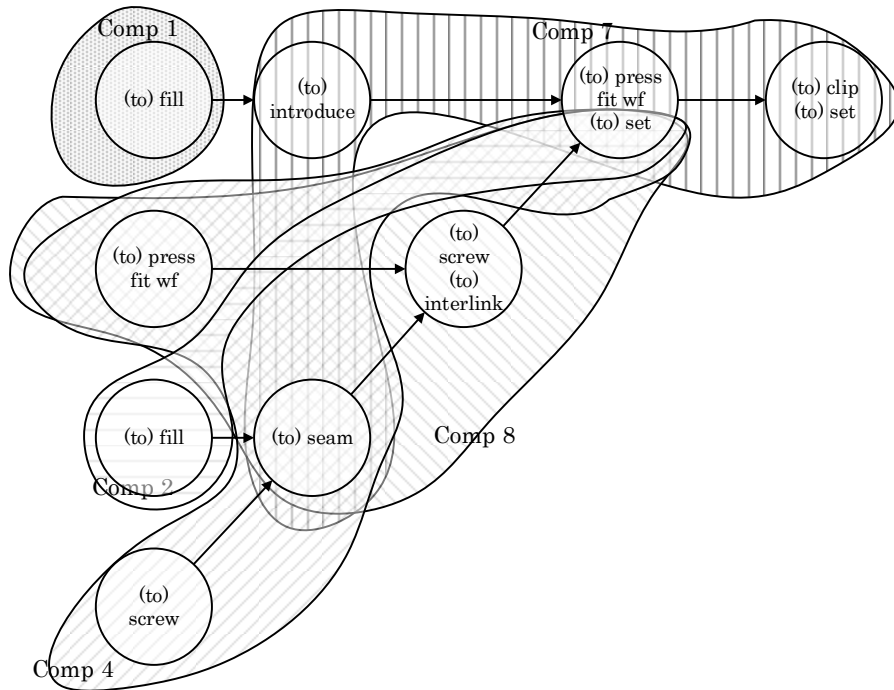


Figure C.5. Precedence location graph for a feather pen

C.7. Preliminary assembly plan

Using the strategy of locating candidate differentiation, and the criterion linear assembly flow, the following preliminary assembly plan has been generated. It represents one possibility to assemble the feather pen.

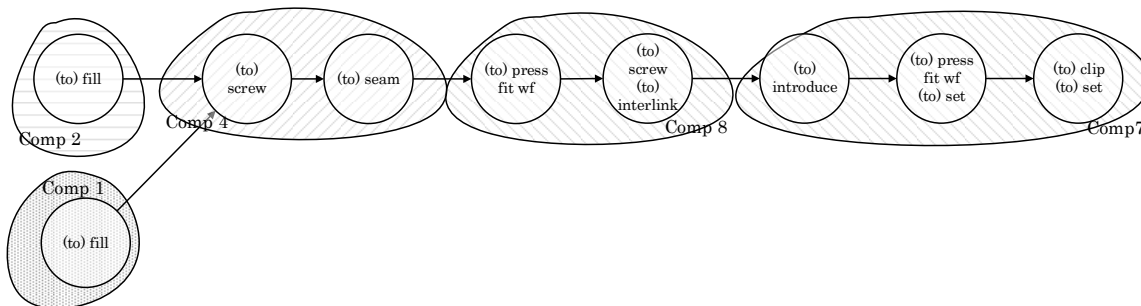


Figure C.6. One preliminary assembly plan for the feather pen

Its DNA representation is as follows (positive x direction for the feather pen is the direction of the feather).

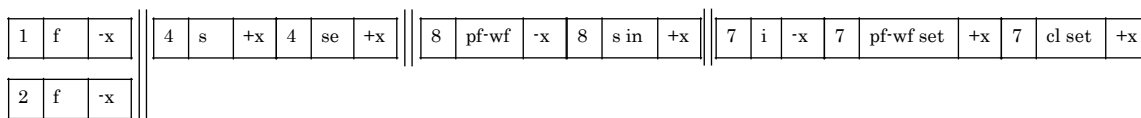


Figure C.7. DNA representation of feather pen assembly

Appendix D. Assembly technology improvement

D.1. Step by step illustration of Example IV.3.2

The enriched DFC model is presented in Figure D.1. The initial design is illustrated in Figure D.2

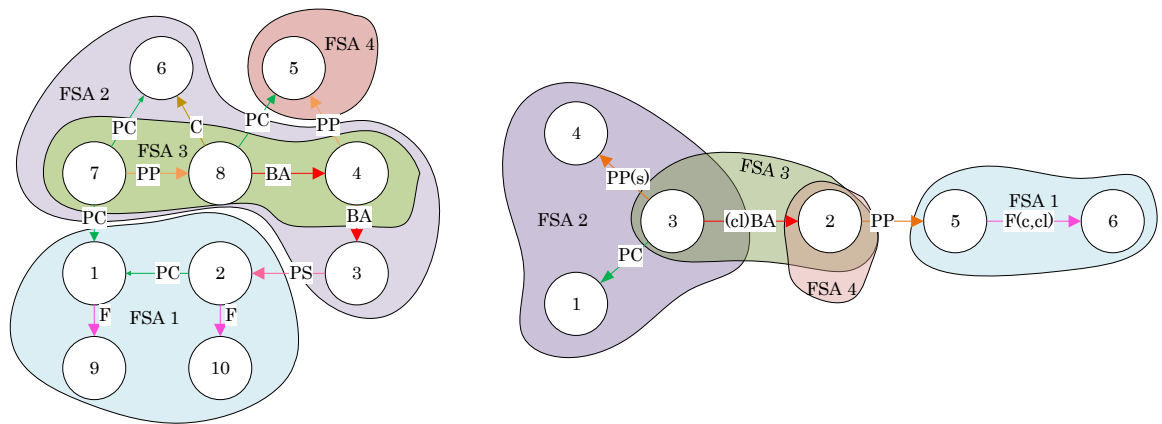


Figure D.1. Initial enriched DFC models

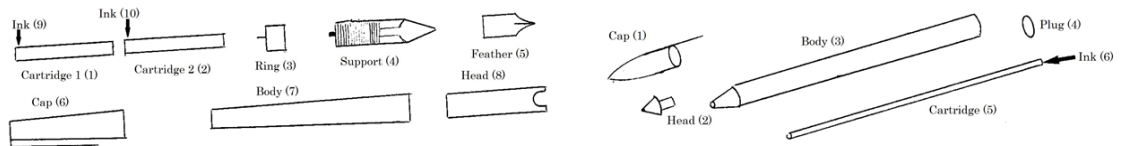


Figure D.2. Feather pen and ball pen – initial design

D.1.1. First iteration

The improvement process starts with FSA₁ ($S_3 = 0,5; S_4 = 0$). The differences in S_3 are due to the fact that the feather pen has two cartridges, one placing the other. Differences in S_4 are due to the two cartridges as one is loose and in contact with the pen body. In addition, the technology for connecting the cartridge to the support is different. Two actions have to be undertaken: first, replace two cartridges by one big one. And second, replace the plastic deformation-seaming technology in the feather pen with the press fitting-plaiting operation of the ball pen. The figures B.3 and B.4 illustrate the enriched DFC and product design after iteration 1.

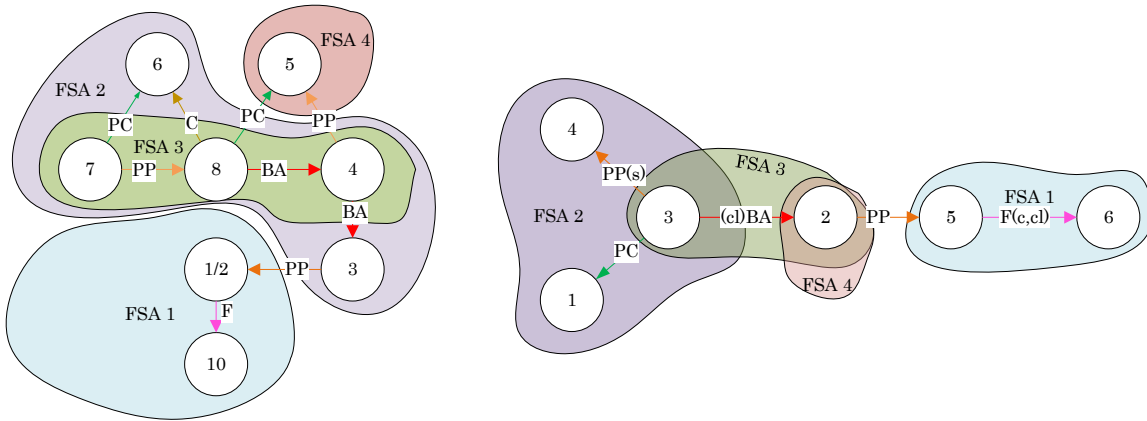


Figure D.3. Enriched DFC after iteration 1

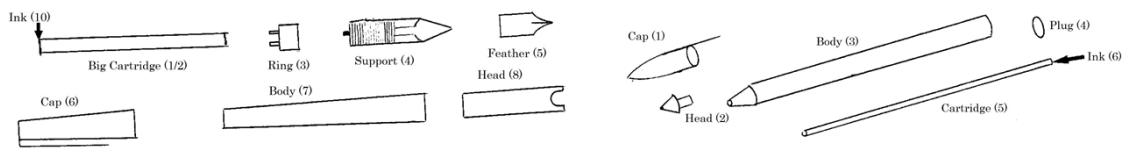


Figure D.4. Modified feather pen (big cartridge and changed ring) after iteration 1

D.1.2. Second iteration

FSA 2 differs only in S₃ as there is no value for S₄ (none). To achieve full similarity, the bolted assembly and clipping technology of the feather pen has to be replaced by press fitting-plaiting. The figures B.5 and B.6 illustrate the enriched DFC and product design after iteration 2.

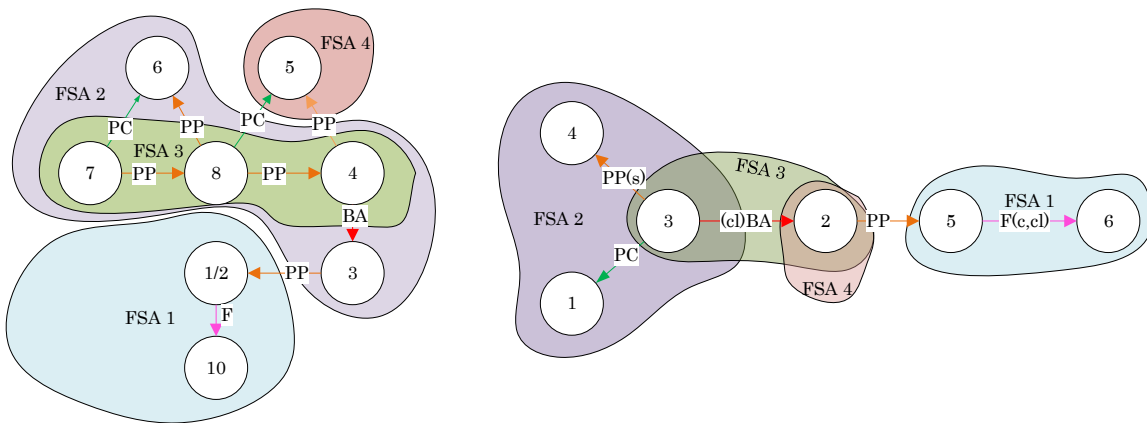


Figure D.5. Enriched DFC after iteration 2

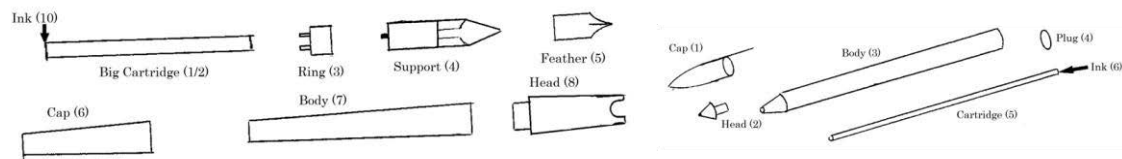


Figure D.6. Modified feather pen after iteration 2

D.1.3. Third iteration

In FSA 3, S₃ is differing by the bolted assembly of the ball pen (the bolted assembly in the feather pen has been changed in the step before). Therefore, it has to be changed to press fitting-plaiting. The figures B.7 and B.8 illustrate the enriched DFC and product design after iteration 3.

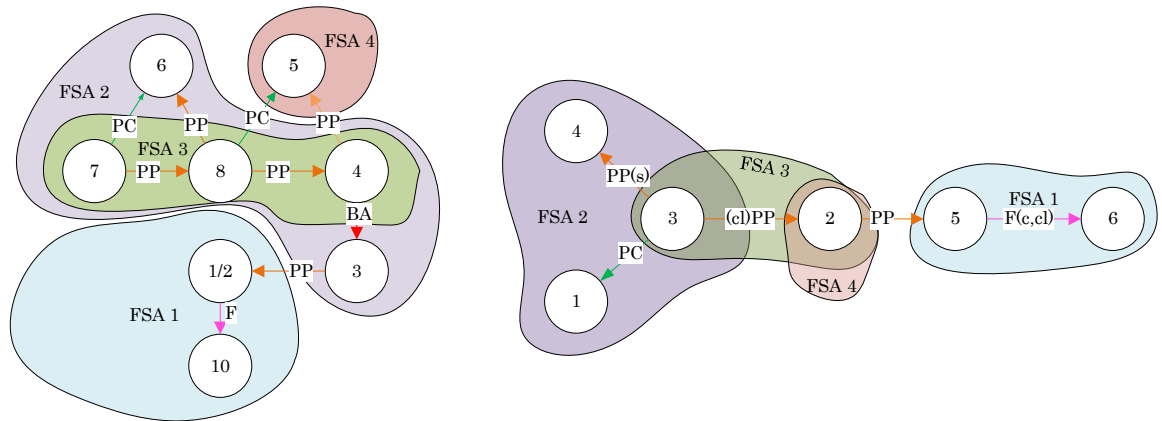


Figure D.7. Enriched DFC after iteration 3

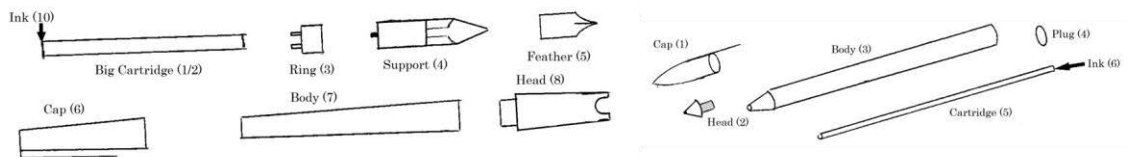


Figure D.8. Modified ball pen after iteration 3

D.1.4. Fourth iteration

For FSA 4, S₄ only has to be treated. The bolted assembly of the ball pen has already been changed to press fitting-plaiting. Only the placing-charging technology in the feather pen has to be changed. Either it is changed to press fitting-plaiting as well or the product design is changed to eliminate the mechanical link. The figures B.9 and B.10 illustrate the enriched DFC and product design at the end of the assembly technology improvement loop.

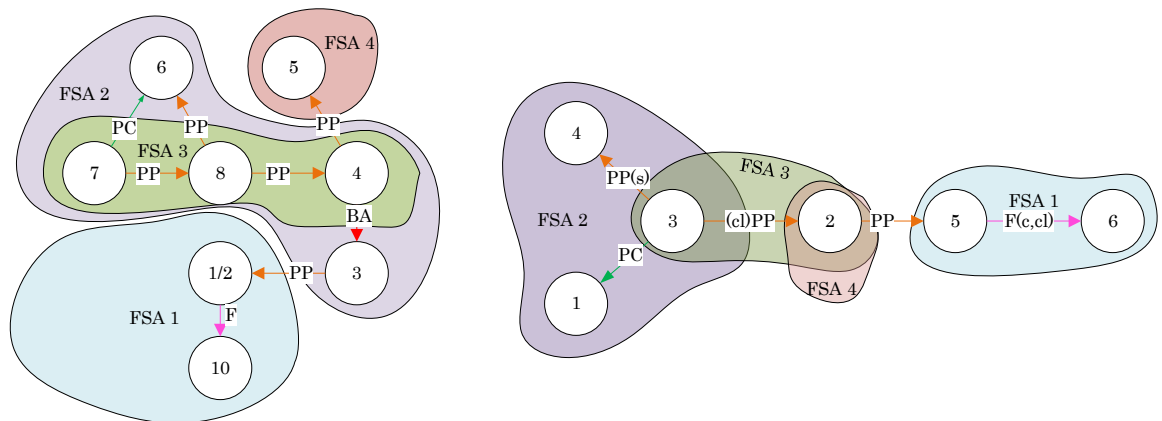


Figure D.9. Enriched DFC after iteration 4

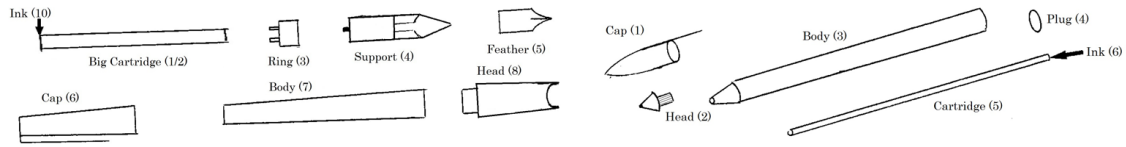


Figure D.10. Final design of ball and feather pen after assembly technology similarity improvement

E.2. Table for extrinsic and intrinsic precedencies

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33				
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Figure E.2. Extrinsic and intrinsic precedence table



Paul Leonard STIEF



TITRE CONTRIBUTION A LA CO- CONCEPTION DE PRODUITS ET DE LEURS SYSTEMES DE PRODUCTION RECONFIGURABLES

Résumé

La thèse propose une méthode supportant la co-conception de produits et de leur processus d'assemblage. Elle structure et guide ainsi l'analyse de la similarité des produits, en termes de : conception et des technologies d'assemblage utilisées, afin de les regrouper dans des familles de produits. Pour ces familles, une nouvelle approche de conception architecturale de leur système d'assemblage est présentée : celle-ci se base sur l'identification des composants servant à la mise en position des sous-ensembles lors d'opérations d'assemblage. Elle permet également de repenser le système de production en fonction des séquences de mises en position, de leurs compatibilités et de l'ordonnancement des opérations par mises en position pour l'assemblage multiproduits. Cette approche permet de concevoir des systèmes de production reconfigurables et d'identifier les opportunités techniques et opérationnelles permettant la conception de systèmes multiproduits. La méthode proposée a été éprouvée avec succès sur plusieurs cas industriels en coopération avec notre partenaire afin d'en montrer l'intérêt.

Mots clés : co-conception produit/processus, système de production, reconfigurabilité

Abstract

The focus of this research work is on proposing a joint analysis of product design and assembly process that analyses the product similarity in terms of design and assembly technology similarity to group them into families. For these product families, a new architectural design approach for their assembly system is presented based on components used to locate subassemblies during the assembly operations. It allows the production system to be redesigned based on locating sequences, locating scheduling and compatible locating schemes for a multi-product assembly. This approach is used to design reconfigurable production systems and to identify relevant opportunities for new multi-product systems. The proposed method is evaluated by case studies in cooperation with the industrial partner.

Keywords: product/process co-development, production system, reconfigurability