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Integrated Product-Process Design Applied to the Selection of Additive Manufacturing Processes

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Preface

This doctoral dissertation is a summary of my research activities conducted during the three years at *Laboratoire de Conception Fabrication Commande* (LCFC) laboratory of Arts et Métiers ParisTech. The PhD research was performed after getting a scholarship from National University of Sciences and Technology (NUST), Islamabad, Pakistan under their Faculty Development Program Abroad – 2015. The funding lasted from January 2016 to February 2019. The aim of the scholarship was to encourage and reward existing faculty for developing their teaching and research skills in key areas of their expertise. The program also focuses on strengthening the university academic programs by paving ways to develop opportunities for research projects for both the partner countries.

The doctoral research focuses to build an integrated approach that can simultaneously handle the product and process parameters related to additive manufacturing (AM). Since, market dynamics of today are constantly evolving, drivers such as mass customization strategies, shorter product development cycles, a large pool of materials to choose from, abundant manufacturing processes, etc., have made it essential to choose the right compromise of materials, manufacturing processes and associated machines in early stages of design considering the Design for AM guidelines. As several criteria, material attributes and process functionality requirements are involved for decision making in the industries, the thesis introduces a generic decision methodology, based on multi-criteria decision-making tools, that can not only provide a set of compromised AM materials, processes and machines but will also act as a guideline for designers to achieve a strong foothold in the AM industry by providing practical solutions containing design oriented and feasible material-machine combinations from a database of 38 renowned AM vendors in the world today.

Because of the international nature of scholarship, the Director General of Arts et Metiers ParisTech authorized, as per decision DG2009-46 of 1er October 2009, 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).

I dedicate this dissertation to my beloved parents and family who taught me to leave a legacy of service to others.

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List of Abbreviations

3DP	3D Printing
ABS	Acrylonitrile-Butadiene-Styrene
AHP	Analytical Hierarchy Process
AM	Additive Manufacturing
ANOVA	Analysis of Variance
APF	Arburg Plastic Free-forming
ASTM	American Society for Testing Materials
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CE	Concurrent Engineering
CJP	Colour Jet Printing
CM	Cloud Manufacturing
DfAM	Design for Additive Manufacturing
DFM	Design for Manufacturability
DLP	Digital Light Processing
DMP	Direct Metal Printing
DOE	Design of Experiments
EBAM	Electron Beam AM
EBM	Electron Beam Melting
FDM	Fused Deposition Modelling
ID	Integrated Design
IPPD	Integrated Product-Process Design
LENS	Laser Engineered Net Shaping
LMD	Laser Metal Deposition
LOM	Laminated Object Manufacturing
MCDM	Multi-Criteria Decision Making
MJM	Multi-jet Modelling
MPS	Material Process Selection
PC	Poly-Carbonate

LIST OF ABBREVIATIONS

PETG	Polyethylene terephthalate glycol-modified
PLA	Polylactide
PP	Poly-Propylene
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
S/N	Signal-to-Noise
SAS	Slide and Separate
SAW	Simple Additive Weighting
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TM	Traditional Manufacturing

Résumé en Français

Conception intégrée produit-processus appliquée à la sélection des procédés de fabrication d'additifs

1. Introduction

1.1 Contexte

Dans l'ère actuelle d'automatisation industrielle accrue, de complexité élevée des pièces, de délais d'exécution de plus en plus courts, de réglementations accrues et remaniées en matière de durabilité, d'introduction de nouveaux modèles d'affaires et de niveaux de débit croissants, la conception d'un produit et le choix du ou des procédés de fabrication doivent être réalisé simultanément (Ahuja et al., 2015). Il a été montré que la partie fabrication de pièce pouvait avoir un impact direct sur le coût (70 à 80 %) et qu'un concepteur devait en tenir compte dès les premières étapes de la conception afin de proposer une solution prenant en compte les aspects de fabrication et les aspects de coûts de montage et de logistique (Budiono et al., 2014; Ranjan, et al., 2015). Ce constat a développé un intérêt pour l'ingénierie simultanée (IS) et la conception intégrée (CI) qui intègre le processus de développement de produits le plus en amont possible afin de tenir compte des exigences externes présents en aval (Loch et Terwiesch, 2000).

Il existe actuellement plus de 80 000 matériaux dans le monde. Les ingénieurs et les entreprises sont constamment à l'affût du "meilleur compromis" pour les matériaux d'ingénierie et les procédés de fabrication afin de satisfaire les besoins des clients et les spécifications fonctionnelles. Traditionnellement, l'approche par essais et erreurs, ou le concept de ce qui était utilisé auparavant, était parfois utilisé pour choisir le matériau et le procédé de fabrication associé. Cette approche doit être repensé aujourd'hui car les technologies de fabrication ainsi que les domaines d'application changent très rapidement chaque jour.

Depuis le début de la fabrication additive (FA) en stéréolithographie (SLA) par systèmes 3D en 1987, la FA a un taux de croissance annuel important de 26,2% pour atteindre un marché de 5,165 milliards de dollars en 2015 (Wohlers, 2016). Avec des technologies émergentes de FA, la suggestion de compromis entre matériaux et procédés de fabrication devient capital [choix couple matériau-procédé (MPS en anglais)]. En s'appuyant sur les notions d'IS et de CI, le matériau et le procédé de fabrication choisis en FA doivent satisfaire aux exigences du cycle de vie du produit imposées par le marketing, la fiabilité, la fabrication, l'esthétique et la qualité.

1.2 Objectifs de la recherche

Les objectifs de cette recherche sont d'explorer les interactions entre les données sur les produits et les processus dans la FA afin de proposer une méthodologie de décision générique qui peut :

a) permettre aux concepteurs de prendre en compte les interactions matériaux-machines-processus dès les premières étapes de la conception

b) prévoir une possibilité de modification de la conception et/ou des exigences pour permettre la fabrication des pièces

c) aider à structurer les connaissances en matière de conception, en particulier aux étapes de la conception conceptuelle

d) Permettre de trouver le meilleur compromis lors de la FA.

L'originalité de cette recherche réside dans la capacité de proposer un compromis entre matériaux de FA, de procédés de fabrication et de machines pour fabriquer n'importe quelle pièce dans n'importe quel domaine d'application. Une base de données de machines FA de 134 machines renommées de 38 fournisseurs internationaux ainsi qu'une base de données de matériaux spécifiques FA sont utilisées pour fournir les combinaisons matériau-machine optimum pour une conception produit. De plus, une approche expérimentale générique est également suggérée pour aider à optimiser les paramètres de processus de la FA.

1.3 Mise en page de la thèse

Cette thèse est divisée en 4 Chapitres et est basée sur les articles publiés par l'auteur (Zaman et al., 2017; Zaman et al., 2018a; Zaman et al., 2018b; Zaman et al., 2018c).

2. État de l’art

Au fil des ans, de nombreuses recherches ont été menées sur le choix des matériaux et des procédés de fabrication et diverses méthodes ont été proposées à cet égard. Cependant, l'examen présenté dans ce chapitre montre clairement que les chercheurs se sont davantage concentrés sur un seul domaine d'application et ont résolu le problème MPS pour une pièce spécifique, plutôt que de suivre un processus générique qui peut traiter tout domaine d'application en adaptant les directives DFM (Design For Manufacturing) aux processus FA. La liberté de modifier les paramètres de conception fait partie intégrante du concept de MPS. Par conséquent, la portée du présent chapitre suit une procédure étape par étape pour mettre l'accent sur quatre grands domaines qui serviront d'étude de base pour aider à établir le plan d'action requis pour la section 3. Dans la première partie, une brève description de la technologie FA et de ses processus associés, en mettant l'accent sur les critères de choix de la technologie FA pour un produit, est discutée. L'étude de l'CIPP en relation avec DFM, DfAM et Design for X (DFX) en ce qui concerne les critères et contraintes de conception communs pour le problème MPS, est présentée dans la deuxième partie. La troisième partie englobe les stratégies de sélection du PDP. Enfin, dans la dernière partie, les limites des trois parties précédentes sont identifiées et des perspectives d'amélioration sont suggérées. Le texte qui suit résume brièvement chacune des parties:

2.1 Fabrication d'additifs : Une vue d'ensemble

Cette section présente un aperçu de la technologie FA en mettant l'accent sur la part de marché atteinte par la FA et ses prévisions. Il traite également des types les plus populaires et les plus courants de procédés, de machines et de matériaux FA en ce qui concerne la classification proposée par le comité ASTM F42. Les différents types de processus FA sont également discutés afin d'intégrer ces informations de notre approche produit-processus intégré ce qui permet de proposer une manière et un moment d'utiliser la technologie FA en fonction de ses capacités. Certaines questions liées à la FA sont également abordées.

2.2 Conception intégrée produit-processus (CIPP) et critères de conception pour les problèmes MPS

Cette section souligne l'importance de tenir compte des paramètres du produit et du procédé dès les premières étapes de la conception. De plus, comme les intervenants de l'industrie de la FA liés à la fabrication de pièces ne modifient pas complètement la conception au cours de la "phase de conception", ceci entraîne une augmentation des coûts engagés en raison de la possibilité de fabrication et du temps de production, il est très important de tenir compte de la relation entre les contraintes de fabrication, les exigences du client et les directives de conception afin que le coût global incluant l'assemblage et la logistique soit réduit. Trois critères de conception : la fonction, le coût et l'environnement sont étudiés en référence à la problématique MPS en mettant l'accent sur la FA. Les lignes directrices de conception relatives à la FA sont également examinées et les facteurs importants sont mis en évidence. Le DOE de Taguchi est également étudié en FA afin de mieux comprendre l'optimisation des paramètres des procédés.

2.3 Stratégies de sélection des matériaux et des procédés de fabrication

Cette section donne un aperçu des stratégies de sélection utilisées dans le SPM, avec un accent particulier sur les techniques MCDM et les méthodes de criblage et de classement associées pour la FA. La sélection optimale des différents processus FA est donc de nature hiérarchique et est catégorisée en fonction de la géométrie, de la technologie, de la performance, de l'économie et de la productivité.

2.4 Analyse des lacunes

La présente section expose les conclusions des trois premières phases et indique que les méthodes proposées dans la documentation sont soit axées sur le point de vue du concepteur, selon lequel la DfAM a été conçue pour aborder la relation entre les données sur les produits et les procédés en utilisant la même méthodologie de haut niveau alors que chaque phase de la DfAM n'était pas claire, soit sur celui du fabricant qui s'est concentré sur la théorie du " pick and choose " avec le AHP comme méthode la plus fiable. De plus, les études étaient soit spécifiques à une fonction, soit spécifiques à une application. Il est donc nécessaire de prendre en compte simultanément les contraintes et considérations de fabrication, les exigences du client, la réserve existante de matériaux FA disponibles et les procédés de fabrication FA correspondants pour optimiser les critères de conception du MPS. Les domaines d'intérêt sont discutés et peuvent être mentionnés en détail dans la version anglaise de la thèse.

3. Projet de méthodologie de décision

La conception des produits intégrant les processus est une approche qui implique l'atteinte des objectifs découlant de l'évaluation des technologies utilisés. L'objectif de compétitivité et la maximisation de la marge bénéficiaire est l'objectif de la plupart des entreprises aujourd'hui, le problème du MPS est donc devenu un effort interdisciplinaire qui nécessite l'apport de toutes les composantes des équipes de conception et de production. Mais comme nous l'avons vu dans l'analyse documentaire de la section 2, il est impératif d'avoir la liberté de modifier la conception d'un produit le plus tôt possible, avant la phase de conception, afin de réduire les coûts de fabrication de ces produits.

De plus, l'incompatibilité entre les matériaux et les procédés de fabrication peut affecter les décisions concernant des paramètres importants tels que la géométrie. Par conséquent, sur la base de la lacune identifiée au chapitre 2, la méthodologie de décision proposée dans ce chapitre suit une procédure étape par étape pour obtenir des combinaisons matériau-processus-machine FA pour un produit lors de la conception. La procédure comporte trois étapes principales : la traduction, la sélection et le classement, et elle est dominée à l'échelle mondiale par les lignes directrices du DfAM et le type de demande. La méthodologie interagit également avec deux bases de données indépendantes, l'une pour les matériaux FA et l'autre pour les combinaisons processus-machine FA. De plus, puisque l'activité de conception peut être divisée en 3 étapes principales, les conceptions conceptuelles, architecturale et de détail, le couplage entre les matériaux, la taille des composants et les processus, l'interaction des coûts entre les processus et les indicateurs de durabilité des matériaux doivent être considérés pour chaque étape. Des stratégies telles que l'approche systémique fondée sur des règles (Zarandi et al., 2011) ont été largement utilisées pour faciliter l'acquisition des connaissances, le choix des critères de sélection, la définition hiérarchique des connaissances, la sélection d'une interface utilisateur et finalement la mise en œuvre. Mais avant tout cela, il est nécessaire de saisir les besoins du client, en termes de spécifications, de préférences esthétiques et de contraintes, de formuler des exigences et des fonctionnalités (Deng et Edwards, 2007).

De plus, pour structurer la hiérarchie décisionnelle, le cadre explore les potentiels de la FA et propose des mesures respectives à l'aide de la littérature examinée. Le cadre général de l'IPPD cible chaque domaine en détail par rapport au MPS, en conjonction avec les étapes de conception associées, c'est-à-dire la conception conceptuelle et la conception architecturale.

3.1 Conception conceptuelle

La conception conceptuelle, dans le contexte de l'CIPP, est considérée comme l'étape clé du processus de conception où le concepteur explore les principes scientifiques fondamentaux, les lignes directrices du DfAM, les contraintes et les relations associées, pour structurer une architecture qui peut être réalisée plus tard dans une conception qui satisfait le besoin. De plus, la structuration efficace de l'énoncé des besoins pour extraire les exigences respectives du produit et du procédé ou l'utilisation de la conception existante pour obtenir les exigences connexes à partir des spécifications fonctionnelles est le point de départ le plus important pour la phase de conception.

De plus, la conception conceptuelle implique la prise de décisions sur divers fronts. La méthodologie proposée a pris en compte trois critères de conception : la fonction, le coût et l'environnement, et chacun de ces critères est associé à des décisions uniques qui servent de " fronts de sélection " pour la prise de décisions dans le MPS. On les appelle respectivement décisions techniques, décisions économiques et décisions de durabilité (Zaman et al., 2018b).

3.1.1 Traduction des exigences

Chaque besoin de produit est un besoin documenté concernant une caractéristique ou une capacité appréciée par les utilisateurs. Dans l'étape actuelle, le concepteur utilise les spécifications fonctionnelles extraites du modèle CAO (y compris les spécifications objectives, l'évaluation de la géométrie, la définition des contraintes, l'identification des variables libres et autres données pertinentes) et génère un ensemble d'exigences qui peuvent être liées à la conception, à la production, au processus de fabrication ou à une combinaison des trois, selon le type de demande et les directives DfAM existantes. Plus précisément, pour le type d'application, un "filtre des applications" a été créé à l'aide d'une revue de la littérature.

3.1.2 Examen préalable des matériaux et des procédés de fabrication en FA

Une fois les exigences approuvées, les tableaux d'Ashby (Ashby, 2010) sont utilisés pour la présélection. De plus, une tâche de fabrication possède des spécifications tels que la densité, le coût, la résistance, etc. et l'objectif est de maximiser ou de minimiser l'un ou l'autre ou certains d'entre eux pour répondre aux besoins fonctionnels de la pièce. Ces indices sont également appelés "indices de performance". Les indices de matériaux suggérés par Ashby (2005) sont utilisés dans la présente thèse pour le criblage des matériaux et procédés de fabrication concernés par la FA.
Comme la collecte des propriétés des matériaux pour divers métaux et non-métaux en référence à différents procédés FA fait partie intégrante de la conception de tout composant (suggéré à la section 2.4), il était nécessaire de structurer une base de données qui puisse contenir ces propriétés. Par conséquent, deux bases de données ont été construites, chacune pour les matériaux et les machines liés à la technologie FA.

Les matériaux FA triés obtenus et les machines FA sont ensuite testés par rapport aux exigences qui sont dominées par les contraintes et les attributs de conception (dérivés des spécifications fonctionnelles). S'ils réussissent le test, l'ensemble des matériaux et des machines est transmis à l'étape de la conception architecturale pour classement.

3.2 Conception architecturale

Lors de l'étape de la conception architecturale une conception est élaborée conformément à des critères techniques et économiques. Dans cette thèse, le choix des matériaux et des procédés est réalisé à l'étape de la conception architecturale afin d'assurer une information préliminaire pour les concepteurs et de réduire les coûts liés à la fabrication. L'étape de la conception architecturale est régie par la procédure de classement des solutions de rechange relatives aux matériaux et aux machines FA examinées (Zaman et al., 2018a).

3.2.1 Classement des matériaux et des procédés de fabrication en FA

Le processus de classement permis par l'application d'outils MCDM et de tout modèle de coût associé pour la sélection de l'ensemble des ressources pour la FA, en fonction des attributs de conception et des contraintes fonctionnelles. La procédure a été validée par (1) AHP classique, qui a été utilisé parce que tous les attributs étaient supposés indépendants, et (2) le modèle de coût adopté par Yim et Rosen (2012). Le résultat du " classement " est un ensemble de compromis acceptable de matériaux FA et de machines de fabrication pour un processus de fabrication FA.

4. Application de l'étude à un cas industriel

Pour valider la méthodologie, on a utilisé une étude de cas industriel basée sur une " grille de perçage" utilisée dans l'industrie aérospatiale pour réaliser des trous avec précision sur les côtés d'un avion. En tant que pratique industrielle conventionnelle, les grilles de perçage sont fabriquées avec des alliages d'aluminium en utilisant des procédés traditionnels d'enlèvement de matière, comme l'usinage conventionnel. En outre, une marge de temps de vingt-quatre heures est disponible pour la conception, la validation et la livraison des grilles dans l'industrie aérospatiale, mais ce délai n'est généralement pas respecté. De plus, comme la pièce n'est pas grande (50 x 50 x 20 x 20 mm), la fabrication sur le site de réalisation des trous (i.e dans à proximité de l'avion) permettra d'économiser du temps, de l'argent et de la logistique. Par conséquent, l'objectif de la présente section était d'évaluer le meilleur compromis possible entre les matériaux et les procédés FA pour la construction de la grille de perçage qui peut répondre aux exigences fonctionnelles et aux contraintes de temps.

4.1 Collecte des données du MPS

Une séance de questions-réponses génériques a été conçue dans le but de recueillir des données pour la traduction des spécifications fonctionnelles. Les questions ont été envoyées par courriel aux experts sélectionnés avant les entrevues. Des entrevues en personne ont ensuite été menées. Les experts ont préféré un matériau non métallique pour la fabrication de la pièce. De plus, les experts ont participé volontairement à cette recherche.

4.2 Criblage des matériaux et des machines FA

Les tableaux et les indices de matériaux d'Ashby relatifs à la maximisation de la résistance et de la rigidité ont été utilisés pour examiner le premier ensemble de matériaux sur la base des spécifications fonctionnelles générées. Les relations fondées sur le module de Young par rapport à la densité, la force par rapport à la densité, le module de Young par rapport au coût relatif par unité de volume et la force par rapport au coût relatif par unité de volume ont été utilisées. L'ensemble de matériaux comprenait des matériaux liés à l'acrylonitrile-butadiène-styrène (ABS), au polypropylène (PP) et au polycarbonate (PC). Chacun des matériaux a ensuite été utilisé pour trouver les matériaux associés dans la base de données des matériaux pour différents processus FA. De même, compte tenu du domaine d'application, à savoir l'aérospatiale, les machines concernées ont également été sélectionnées à partir de la base de données des machines. Nous avons au final obtenu une liste de matériaux, de procédés et de machines FA utilisables.

4.3 Classement des matériaux et des machines FA

L'AHP a été réalisé. DIGITAL ABS, RGD 450, PC, PC ISO, Nylon 6, RGD 875 et ULTEM 1010 ont été choisis comme matériaux utilisables. Ces matériaux ont été associés avec les machines compatibles : les machines Fortus 250 mc, Fortus 380 mc/450 mc, Fortus 900 mc et Objet 1000 Plus. Par conséquent, le MPS final pour la grille de forage comprenait la machine FA'Fortus 900 mc' fonctionnant suivant le Procédé 'FDM' et pouvant utiliser le Nylon

6, ULTEM 1010, PC et PC ISO comme matériaux de construction FA. L'ensemble final des matériaux s'est avéré être un bon compromis pour la construction de la grille de forage.

4.4 Analyse comparative et validation

Pour comparer et valider la méthode proposée au chapitre 3, la même étude de cas (grille de perçage) a été utilisée et appliquée à une autre méthode MCDM populaire pour la sélection des matériaux et des procédés ; la pondération additive simple (SAW). De même, le MPS final pour la grille de forage comprenait la machine FA'Fortus 900 mc' fonctionnant sur le procédé 'FDM' et pouvant utiliser ULTEM 1010 comme matériau de construction FA. Le matériel produit est conforme à celui produit avec AHP.

5. Optimisation des paramètres de processus pour le FDM

Le chapitre 4 a montré l'application de la méthodologie proposée dans une étude de cas industriel (grille de perçage) en suggérant le MPS approprié (matériau, procédé et machine) au niveau du système. Néanmoins, la FA est une technologie efficace, mais au fil des ans, l'application à grande échelle a été plus lente en raison des problèmes de compatibilité entre les matériaux et les machines (Pilipovic et al., 2009 ; Zaman et al., 2018a). Deux voies peuvent être suivies pour surmonter cette situation : premièrement, développer de nouveaux matériaux qui sont non seulement supérieurs aux matériaux conventionnels, mais qui sont également compatibles avec la technologie FA spécifique ; et deuxièmement, ajuster les paramètres du procédé pendant la phase de fabrication afin d'améliorer les propriétés de la pièce produite. La deuxième approche a été suivie avec beaucoup de succès au cours des dernières années, car les propriétés des pièces construites dépendent fortement du " réglage " des paramètres de procédé utilisés (Jain et al., 2009 ; Chockalingam et al., 2008).

Comme le FDM a été choisi comme processus à utiliser pour construire la grille de perçage au chapitre 4, l'objectif de la présente section était d'évaluer l'impact des paramètres du processus FDM sur la résistance des pièces construites en utilisant le plan d'expériences (DOE) de Taguchi. 2 DOE ont été conçus. Le premier DOE a été réalisé avec un matériau polylactide (PLA) sur une machine MakerBot Replicator 2X FDM et le deuxième DOE a été réalisé avec un matériau polyéthylène téréphtalate modifié au glycol (PETG) sur une machine Open Edge HDE. De plus, la méthodologie est de nature " générique " et peut être utilisée pour optimiser divers critères de conception. Nous avons la possibilité de modifier les paramètres du processus et les réglages correspondants si les résultats ne sont pas conformes aux spécifications fonctionnelles.

5.1 Identification des paramètres du procédé et des réglages pertinents.

La procédure commence par l'identification des paramètres du procédé (facteurs de contrôle) à l'aide des spécifications fonctionnelles extraites du modèle CAO. Sur la base de la littérature la plus récente, les " paramètres de travail " concernés ont été choisis en fonction de l'épaisseur de la couche, la peau extérieure, du motif de remplissage et du pourcentage de remplissage. La méthodologie spécifie ensuite les niveaux (paramètres) des facteurs de contrôle à optimiser. De plus, sur la base des facteurs de contrôle et des réglages choisis, le réseau orthogonal (OA) de Taguchi approprié est conçu (voir Tableau 5.3).

5.2 Expériences

Pour les deux DOE, 8 expériences ont été réalisées à chaque fois pour produire des grilles de perçage avec chaque matériau (PLA et PETG). Une fois les pièces construites avec chaque expérience, des essais de compression ont été effectués pour les 16 échantillons (8 pour chaque expérience) pour un déplacement donné de 3 mm avec une vitesse d'impression de 1 mm/min (ASTM, 2015) pour chaque échantillon.

5.3 Calcul du rapport signal/bruit (S/N) et analyse de variance (ANOVA)

Le rapport signal/bruit est utilisé pour déterminer la robustesse d'une conception. Comme l'objectif est de maximiser la force de compression, on utilise la caractéristique " plus grand le meilleur ". L'analyse de variance est également appliquée aux résultats.

5.4 Résultats

Les résultats des 1er et 2e DOE sont présentés. Les données ont été analysées à l'aide du logiciel Minitab-17. L'analyse du rapport ANOVA et du rapport signal/bruit a également été effectuée pour déterminer la combinaison optimale des paramètres de procédé. Les résultats concluent que la force de compression est surtout influencée par le pourcentage de remplissage pour les grilles de forage à base de PLA et PETG. Elle est suivie du nombre de peau extérieures, de l'épaisseur de la couche et du motif de remplissage pour la grille de perçage PLA ; et du motif de remplissage, du nombre de peau et de l'épaisseur de la couche pour la grille de forage PETG. Ainsi, les résultats ont révélé que la combinaison de $A_2B_2C_2D_2$ pour les deux DOEs, c'est-à-dire l'épaisseur de couche (A) de 0,2 mm, le nombre de peau (B) de 4, le motif de remplissage (C) de diagonale et le pourcentage de remplissage (D) de 70%, étaient les paramètres optimum pour obtenir une force de compression optimale.

6. Conclusion

L'intégration d'une approche d'intégration produit process lors de développement de produits s'inspire de l'ingénierie concourante et fournit des résultats sous la forme d'une réduction des coûts, d'une amélioration des performances fonctionnelles et de la durabilité. Étant donné que 70 à 80 % des coûts sont engagés en raison des choix de fabrication de la pièce, il est nécessaire d'offrir une certaine souplesse pour modifier les paramètres du procédé dès le début de la phase de conception. De plus, comme il existe aujourd'hui de nombreux matériaux disponibles avec différents procédés de fabrication, il est impératif de choisir la combinaison la mieux adaptée pour fabriquer une pièce en MPS. Par conséquent, il était nécessaire d'élaborer une méthodologie générique qui puisse tenir compte de tous les domaines d'application pour divers critères de conception. La méthodologie doit également pouvoir prendre en compte les directives DfAM disponibles pour générer les exigences et les attributs nécessaires à la fabrication d'une pièce.

Par conséquent, une méthodologie de décision générique, basée sur les tableaux de sélection des matériaux et les MCDM d'Ashby, a été présentée dans cette recherche doctorale afin de suggérer le meilleur compromis entre le(s) matériau(s), le(s) procédé(s) de fabrication et les machines pour la technologie FA. L'étude a été une tâche de conception approfondie et a travaillé intensivement aux étapes de la conception et de la conception architecturale. Une base de données de machines FA de 134 machines renommées de 38 fournisseurs internationaux ainsi qu'une base de données de matériaux spécifiques FA ont également été utilisées pour fournir le MPS le plus pratique.

Une étude de cas industrielle de l'industrie aérospatiale a été utilisée pour valider la méthodologie. Il était basé sur une " grille de perçage " qui permet de percer des trous sur les côtés d'une carrosserie d'avion avec précision. La machine, Fortus 900 mc, fonctionnant selon le procédé FA 'FDM' a été choisie pour fabriquer la pièce. La machine peut utiliser le Nylon 6, ULTEM 1010, PC, PC ISO et PPSF/PPSU comme matériaux de construction. Les matériaux ont également été classés et chacun s'est vu attribuer une note basée sur les attributs des matériaux définis pour l'AHP.

De plus, comme l'optimisation des paramètres de procédé est l'une des tâches de conception les plus critiques, une méthodologie générique axée sur les chapitres a été proposée au chapitre 4 pour optimiser les paramètres de procédé liés à la FDM. Le DOE de Taguchi a été utilisé et la combinaison optimale des paramètres du procédé a été suggérée, chaque expérience ayant un matériau et une machine différents.

English Version

Section 1

Introduction and Research Objectives

Chapter 1: Introduction

1.1 Background

In today's era of increased industrial automation, high part complexity, shorter lead times, increased and revamped regulations on sustainability, introduction of new business models, and rising throughput levels, the design of a product and the selection of fabrication process(es) must be simultaneously pursued (Ahuja et al., 2015). As manufacturing is no more just about constructing physical products, changes in consumer demands, economics of production and nature of products are some of the most important decisions in the manufacturing industry which are made during engineering design (Whitney, 1988). It has been highlighted that the manufacturability of any part has a direct impact on the cost (70-80%) and a designer should cater for it in the early stages of design and subsequently provide a platform that is both easy to follow in terms of manufacturing and leads to reduced costs of assembly and logistics (Budiono et al., 2014; Ranjan, et al., 2015). The subsequent realization has led to the interest in Concurrent Engineering (CE) and Integrated Design (ID) which integrates product development process with the participants that make upstream decisions to consider downstream and external requirements (Loch and Terwiesch, 2000).

The concurrent design requires an integration of design & manufacturing, and an 'optimization' process that will consider design trade-offs related to product performance (i.e., productivity), producibility, utilization and support. Past-experience has indicated that there are several benefits of CE and ID including 30% to 70% less development time, 65% to 90% fewer engineering changes, 200% to 600% higher quality, 20% to 90% less time to market, and 20% to 110% higher white-collar productivity[1]. It is also important to understand that the freedom to change the design is decreased considerably as the design matures from the preliminary level to full scale production (Marx et al., 1994). Therefore, it is significant to have the freedom to modify product development process in the design phase to achieve a reduction in product development time, production costs, and quality defects. Conceptual process planning has been

[1] Society of Concurrent Engineering (SOCE), Seattle, WA, 2001.

considered to estimate the manufacturability and cost of conceptual design in early parts of the design stages (Hassan et al., 2010).

The idea explained above is also referred to as Design for Manufacturability (DFM); developed by Stoll in 1988 to simultaneously consider the design goals and constraints in part manufacturing and is typically conducted with a manufacturing process in mind. DFM is a branch of Design Theory and Methodology (DTM) methods. Here, the design theory relates to how to model and understand design, while the design methodology (scope of the thesis) explains the design process model incorporating all relevant specifications (Yang and Zhao, 2015). A potentially important decision making concerning DFM is the selection of materials and manufacturing processes.

Tentatively, over 80,000 materials exist in the world. Engineers and companies are on a constant look out for selection of the 'best compromise' for engineering materials and manufacturing processes to satisfy the customer needs and functional specifications. Many of the 'traditional materials' which have served the manufacturing sector for so long are being replaced by 'new materials' due to constant variations in the design goals such as performance, size, weight and topology optimization (Tang, et. al, 2011; Farag, 2002). Moreover, constraints (which can either be function or process specific or both) must be accounted for in the design phase to achieve the required result. Traditionally, trial and error approach or the concept of what was used before, was used at times to select the material and associated manufacturing process. This approach can't be followed today because the streams of manufacturing technologies as well as the areas of application are dynamically changing every day.

Since the inception of Additive Manufacturing (AM) as Stereolithography (SLA) by 3D systems in 1987, AM has taken up a significant and impressive compound annual growth rate of 26.2% to attain a market worth of $5.165 billion in 2015 (Wohlers, 2016). The dynamic market factors have further assisted the associated growth of AM and it can potentially replace conventional methods to produce parts when production volumes are small (Barlier and Bernard, 2016; Campbell, et al., 2012). DFM guidelines well cover the Traditional Manufacturing (TM) processes where to have a good design, the factors majorly accounted for include developing a modular design, using standard components, designing the parts in a way that they have multiple uses, avoiding separate fasteners, minimizing assembly directions, maintaining uniform wall thickness, and avoiding sharp corners (Kuo et al., 2001). But many of these factors and manufacturing constraints are lessened and even vanished in majority when it comes to AM which can produce parts of any geometric complexity without TM aids such as tooling (Hague et al., 2003; Hopkinson and Dickens, 2006). Since AM has the capability to operate potentially constraints free, it has invited new heights of design freedom by offering enhanced complexities in terms of shape, multi-scale structures, materials and functionality (Rosen, 2007). In addition, the quantity and variety of End-of-Life (EoL) products in recent years has demanded the AM production systems to be designed in a sustainable manner where parts are built in a single operation without wasting much raw material (Vayre et al., 2012) such that the economic and environmental impacts are reduced (Le et al., 2015). This also includes the need for post-processing for issues such as removal of powder, support structures, platforms and polishing, as the surface quality may limit the application of the part produced (Alfieri et al., 2017).

Accordingly, the existing vast field of processing technologies and competitors in the hardware space of AM have all been found chasing diverse goals to simultaneously design a product, select a compromised material and pick a suitable fabrication process. AM, therefore, has the potential to radically change the way in which many products are made and distributed. This also suggests that AM may truly become a 'disruptive' technology. Various researches in literature have worked on methodologies to refine conventional DFM with AM design criteria (Yang and Zhao, 2015; Kerbrat et al., 2011; Hague et al., 2004). For example, design guidelines in terms of geometric possibilities and cost, such as rethinking the whole assembly towards integrated free form design, using as little raw material as possible to optimize the design towards highest strength and lowest weight, utilizing undercuts and hollow structures, and designing the optimal shape of the part according to the functionality, have taken the Design for Additive Manufacturing (DfAM) to a whole new level (Atzeni et al., 2010).

As far as the areas of application are concerned for the AM-related parts, Cotteleer et al. (2013) and Sharon (2014) divided them into seven areas: aerospace; motor vehicles; health care; consumer products/electronics and academic institutions; industrial applications; architecture; and government/military. Each of these applications have different 'generic' functionality indices and weights concerning multiple design goals such as cost, material strength, energy consumption, environmental impact, and recyclability, etc. For instance, the consumer electronics industry focuses generally more on reduced cost than material strength, whereas for the aerospace industry, performance and material strength have greater importance than cost.

The suggestion of the compromised materials and manufacturing processes, referred to as the Material Process Selection (MPS) problem from now on, becomes an interdisciplinary effort keeping in view AM's capacity to be both highly inclined towards CE / ID and governing multiple areas of application. Although many AM design guidelines have been published to cater for the process and machine specific constraints for a material, such guidelines could only provide a starting point and do not provide information about the different kinds of AM machines and their production capabilities (Thompson et al., 2016). Also, AM machines have different architectures and material processing capabilities (Ituarte et al., 2015). Furthermore, material properties, geometrical stability, and topological quality of parts produced by AM highly rely on the manufacturing process planning and machines architecture (Hu and Kovacevic, 2003). Hence, the chosen material and manufacturing process in AM should satisfy the product's lifecycle requirements enforced by the design engineering, marketing, reliability, manufacturing, aesthetics and quality. For example, mechanical or physical properties are the material attributes critical for material selection while for the manufacturing process selection, geometric, technological, and production properties are important as they are linked with functional requirements (Giachetti, 1997).

MPS problem requires input from various corners such as industrial engineering, material science and engineering, and mechanical engineering (Jahan et al., 2010). It involves several conflicting objectives and can be best solved using Multi-Criteria Decision Making

(MCDM) methods (Deng and Edwards, 2007). The idea is to get one solution which is a good compromise and acceptable to the entire team. Furthermore, with regards to process planning for AM, tasks such as build orientation and support structures must be considered and synced to the optimization and/or decision-making methods. For the former parameter, factors such as part's height in the build direction, surface roughness, area of base on which the part rests and mechanical properties of the part must be considered while for the latter, part geometry and material play a great role (Kulkarni et al., 2000). Each of the factors discussed above further lie under prescribed design criteria such as function, cost and environment.

Additionally, as explained above, produced parts in an AM process must concurrently achieve different kinds of dimensional and mechanical requirements. But frequently, due to the orthotropic behavior of the AM process and the process dependencies of the additive method, the manufacturing set up imply trade-offs not only amongst micro and macro level geometrical requirements but also in mechanical requirements. To cater for such issue, Design of Experiments (DOE) has been utilized to optimize individual manufacturing parameters of the machines (Hsu and Lai 2010; Rahmati et al., 2007; Wang et al., 2007).

1.2 Research Aims

The aims of this research are to explore the interactions between product and process data in AM to propose a generic decision methodology that can:

(a) facilitate designers in providing design oriented and feasible material-machine-process combinations in early stages of design
(b) provide window for modification of design and/or requirements, and allow re-manufacture of parts
(c) assist in structuring of design knowledge especially in conceptual design and embodiment design stages
(d) offer not the best but rather compromised recipe for making a part with AM in terms of MPS.

The generic decision methodology will enable:

(a) designers in AM industry to get first-hand information on MPS early in the design phase to minimize cost of manufacturability

(b) applicability in all areas of applications.

1.3 Research Objectives

To achieve the research aims in Section 1.2, research objectives have been identified as follows:

(a) Review the state of the art for Integrated Product-Process Design (IPPD) in AM MPS along with identification of research gaps
(b) Design a new generic decision methodology for MPS in AM based on the research aims, literature review and identified gaps. The methodology will not only be able to consider the interaction between product and process data but will also be applicable on all areas of application using the MCDM methods. The methodology will consider product requirements, attributes and other function-related constraints and objectives
(c) Evaluate the performance of proposed methodology with the help of a detailed industrial case study and discuss the conclusions drawn
(d) Devise a systematic experimental approach to study the influence of different process parameters in AM on certain design attribute(s) for the selected industrial case study.

The novelty of this research lies in the capability to provide a compromised set of AM materials, manufacturing processes and machines to manufacture any part from any area of application. An AM machine database of 134 renowned machines from 38 international vendors along with AM-specific materials' database is utilized to provide the most feasible material-machine combinations for a given design of product model. In addition, a generic experimental approach is also suggested to help in optimizing the process parameters for AM.

1.4 Layout of the thesis

This dissertation is divided into 4 sections and is largely based on the papers published by author (Zaman et al., 2017; Zaman et al., 2018a; Zaman et al., 2018b; Zaman et al., 2018c). The layout is illustrated in Figure 1.1. Section 1 discusses the background of the problem at hand along with research aims, objectives and layout of the thesis. Section 2 presents the detailed literature review of the IPPD concept in conjunction with DfAM and its subsequent relation with MCDM techniques related to MPS problem. Section 3 encompasses the theoretical and experimental research of the thesis and is composed of 3 chapters (3, 4 and 5) and 2 levels (1 and 2). Level 1 contains Chapter 3 and 4 showing the proposed methodology with an application on industrial case study from aerospace industry along with a comparative analysis with another MCDM tool [Simple Additive Weighting (SAW)], while level 2 incorporates Chapter 5 demonstrating the experimental approach which utilizes Taguchi's DOE to discuss the results obtained to study the impact of AM process parameters on design attributes. Chapter 5 proposes a chapter-centric methodology that can be included in the global methodology (Chapter 3) of the thesis. The last section, i.e., Section 4 discusses the conclusions drawn for a collaborative product development (considering product and process development) and sums up the dissertation along with avenues of future work.

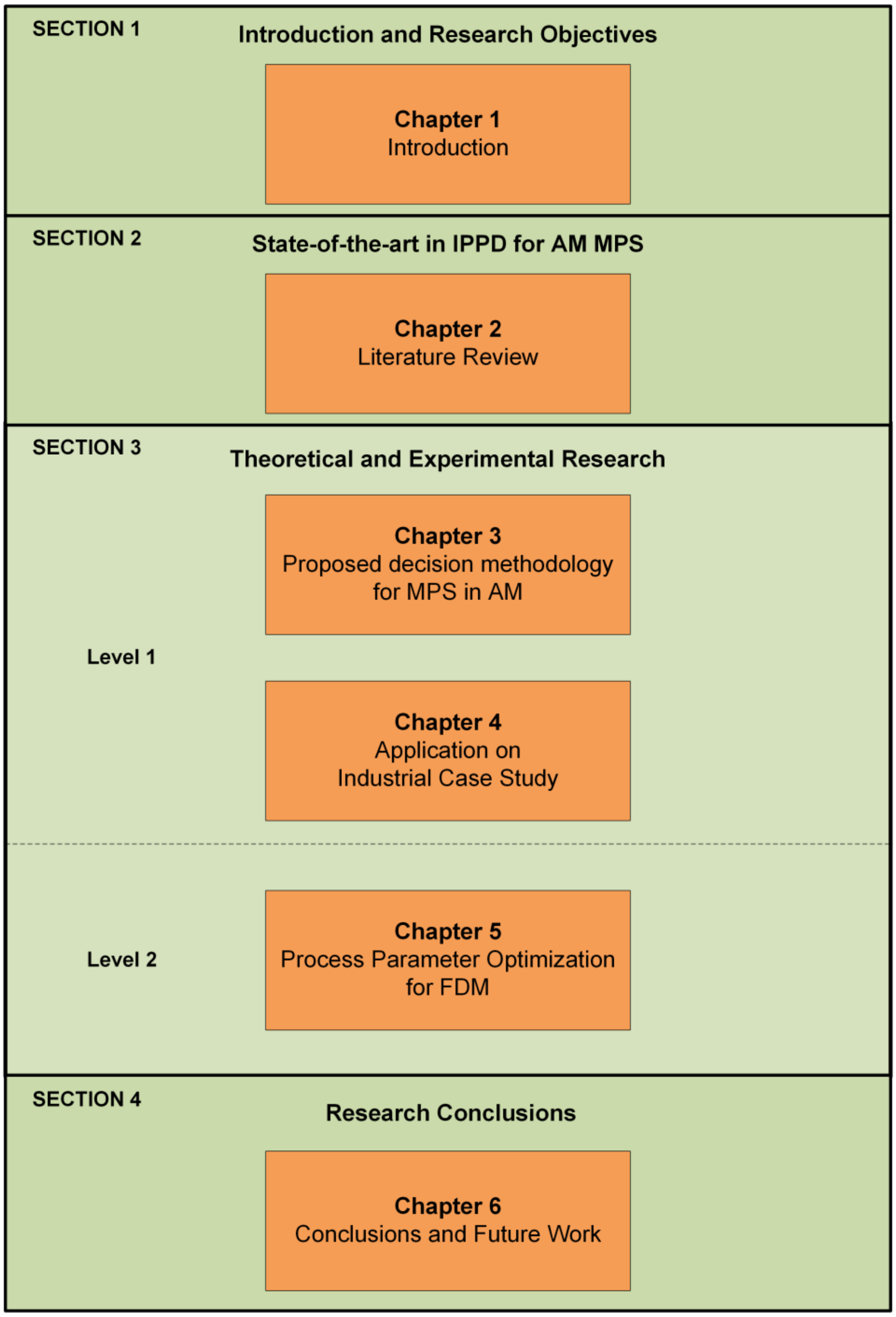


Figure 1.1. Structure of dissertation

Section 2

State-of-the-art in IPPD for AM MPS

Chapter 2: Literature Review

A considerable amount of research has been carried out on material and manufacturing process selection over the years and various methods have been proposed in this regard. However, the review presented in this chapter shows clearly that the researchers focused more on a single area of application and solved the MPS problem for a specific part, rather than following a generic process that can handle any area of application by moulding the DFM guidelines to suite AM processes. The freedom of changing the design parameters is integral to the concept of MPS. Therefore, the scope of this chapter follows a step by step procedure to focus on four major areas that will act as background study to assist in reaching the required course of action for Section 3. In the first phase, brief description of AM technology and its associated processes with focus on the criteria of choosing AM technology for a product is discussed. The study of IPPD in relation with DFM, DfAM and Design for X (DFX) with respect to common design criteria and constraints for MPS problem, is presented in the second phase. The third phase encompasses MPS selection strategies. And finally, in the last phase, the research gap from the previous three phases is identified and retrofit measures are suggested as a research direction for the subject thesis. To summarize, the focus areas are mentioned below for quick reference:

1. Additive Manufacturing: An Overview
2. Integrated Product-Process Design (IPPD) and design criteria for MPS Problem
3. Material and Manufacturing Process Selection Strategies
4. Gap Analysis

2.1 Additive Manufacturing: An Overview

AM is defined by the American Society for Testing Materials (ASTM) as the "process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing technologies like traditional machining" (ASTM, 2012). STL (STereoLithography or Standard Tessellation Language) is the standard file format used on various AM machines but there are other file formats such as SLI, SLC, HPGL, CLI, VRML, 3MF and IGES. The idea is to fabricate a solid geometry by depositing material in an additive manner. Hence, there is a fundamental difference between this technology and other traditional manufacturing technologies such as machining (subtractive) or casting (deformation). The synonyms used in literature for AM include additive techniques, layered manufacturing, additive layer manufacturing and free form fabrication (Mellor et al., 2014). The generic AM process is shown in Figure 2.1.

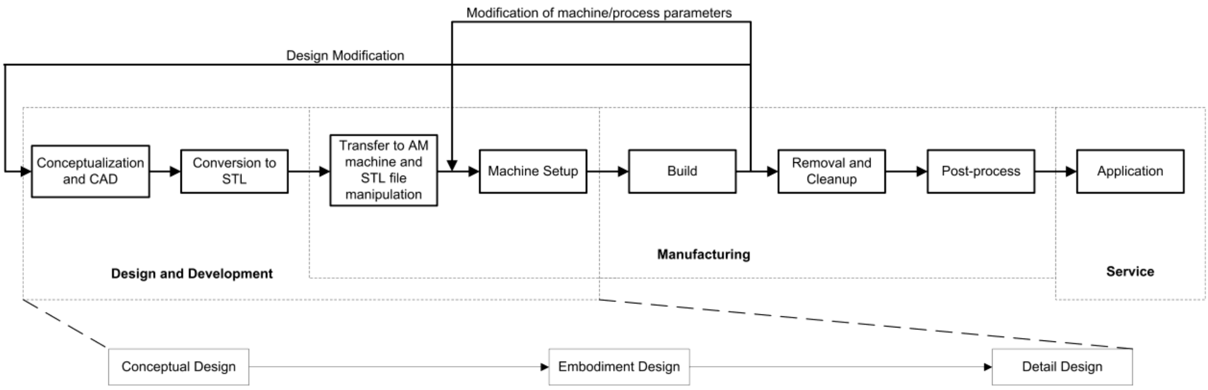
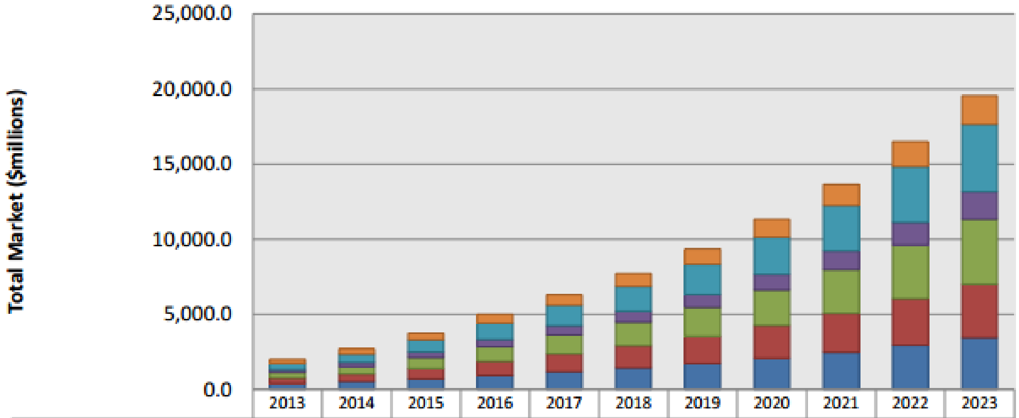


Figure 2.1. Generic AM Process (modified from Gibson et al., 2015)

The generic AM process starts with a software model that can fully depict the external geometry of the part followed by conversion to the STL file format. The software can be any CAD solid modelling software, but the output must be a 3D solid or surface representation. This file type describes the external closed surfaces of the CAD model drawn and forms the basis for the calculation of the slices. Just as 3D CAD is becoming like What You See Is What You Get (WYSIWYG), the same notion goes with AM and it can be easily understood that in this case What You See is What You Build (WYSIWYB). The next step involves transfer of the file to the AM machine and if necessary, to undertake manipulation to correct the size, position and orientation of the part to be built. The first three stages were encompassing the product at hand but the fourth step, i.e., machine setup, is critical for building of the part and hence involves the process at disposal. Build parameters like material constraints, layer thickness, energy source, build time, etc., are considered at this stage. Since, the world has moved towards CE and IPPD, the first 4 steps of the generic AM process are considered part of ‘design and development’. The building of the part is an automated process and doesn’t require much supervision unless deemed necessary. This implies the seamlessness of the process where the number of process steps are reduced and building of the part can (if possible) be done in one single step. Once, the part is built, it is removed from the machine and post processing operations are conducted if the part requires additional clean up. Parts at this stage maybe weak and may require removal of support structures manually by experts at handling of the parts. Steps 3 and 4 of the generic process also overlaps with the ‘manufacturing’ division thereby further strengthening the presence of IPPD. Last, the part(s) built are used in the required application either individually or collectively as part of an assembly, etc. (Gibson et al., 2015).

AM techniques have evolved steadily over time after they came in to the limelight as SLA for the first time in 1987 (Wohlers, 2014). AM is now part of industries ranging from aerospace to dentistry and from automotive to made-to-fit clothes. According to Wohlers (2016), the global AM industry (all AM services and products worldwide) grew an impressive 25.9% (CAGR) to USD 5.165 billion in 2015. It is further expected to grow to USD 12.8 billion in 2018 and exceed USD 21 billion worldwide by 2020. This also suggests that if AM has a saturation level of (5 to 35) % of the areas of application (aerospace, automotive, medical, etc.), it might reach 50% of the total market potential between 2031 and 2038, and even 100% between 2058 and 2065 (Thomas, 2013). SmarTech (2014) forecasted the total market for AM by industry type and concluded that the education/personal, aerospace, medical and dental industries will be the largest players in the global market in the next decade for AM. The forecasts are shown in Figure 2.2.



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Other (millions)	277.5	325.7	443.1	572.3	703.3	844.3	1,001.5	1,187.9	1,400.3	1,654.0	1,902.6
Personal/Education (millions)	421.5	568.6	810.5	1,088.2	1,369.1	1,639.5	2,009.6	2,472.5	3,031.2	3,719.2	4,480.7
Auto (millions)	194.8	264.1	365.6	483.1	606.1	736.7	872.1	1,037.9	1,240.3	1,503.3	1,819.3
Dental (millions)	352.9	509.0	721.7	978.0	1,256.6	1,565.5	1,926.5	2,371.5	2,906.9	3,570.8	4,312.9
Medical (millions)	362.8	489.2	686.2	929.0	1,199.6	1,476.1	1,799.3	2,173.1	2,595.1	3,089.1	3,572.0
Aerospace (millions)	412.5	535.3	722.6	945.2	1,181.2	1,447.2	1,736.8	2,083.1	2,478.6	2,956.2	3,451.0

Figure 2.2. Forecasts for AM Market by Industry (SmarTech, p-13).

AM processes are particularly compatible with concept models of low volume production end-usable products (Khorram and Nonino, 2017). Each of the industries in Figure 2.1 are utilizing AM in three main categories based on the end use for the produced parts, i.e., Rapid Prototyping (RP), Rapid Manufacturing (RM) and Rapid Tooling (RT). According to Armillotta (2006) and Zhang and Liu (2009), RP is used to produce prototypes that can be further utilized for design verification, functional testing and marketing. Shorter product development times and lower costs are the main advantages of RP. Moreover, RM focuses on the customers and produces parts that can be readily used by the consumers (Hague et al., 2003; Levy et al., 2003). RT, the last of the categories, is used to produce a tool or a die. Examples include patterns for sand and investment casting, moulds for injection molding and tools for electrical discharge machining (Dippenaar and Schreve, 2012; Nagahanumaiah et al., 2008; Pal and Ravi, 2007). Sculpteo (2017), further, revealed that proof of concept (34%), prototype (23%) and production (22%) are the three most common reasons why companies around the world are moving towards the AM oriented solutions. Figure 2.3 shows the global trend.

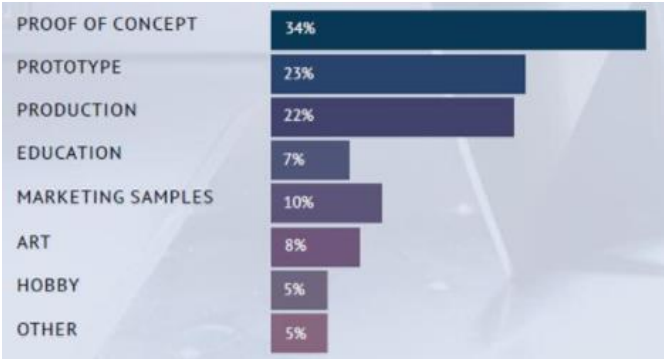


Figure 2.3. Reasons for pursuing AM (Sculpteo, 2017)[2].

To choose AM technology as an alternative to conventional processes requires it to be competitive in terms of processing time. Although it is difficult to predict when exactly AM will become competitive in this case, but it has evolved over the years appreciatively. Figure 2.4 shows the trend in terms of an approximation of the days required for additively manufacturing the components of a car. The results were obtained from the best available commercial DMLS machines used in four periods (2004, 2010, 2013, and 2014). The machines produced the same amount (135,000 cm^3) of parts made of steel materials. It is clearly noticeable that from 2004 to 2014, time to produce decreased from 780 days to 144 days, thereby, resulting in a 450% improvement. This is due to the increased rate of material deposition per hour of the current machines. The same trend can be forecasted on other machines and areas of applications.

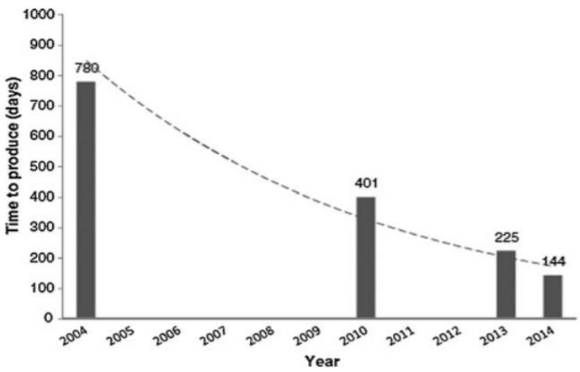


Figure 2.4. Estimated days to 3D print the steel parts of a passenger car on a single selective laser melting 3D printer (Holmström et al., 2016)

[2] https://www.forbes.com/sites/louiscolumbus/2017/05/23/the-state-of-3d-printing-2017/#143771a857eb

Moreover, AM has been classified based on various factors in the literature. Gibson et al. (2015) suggested that some authors use 'baseline technology' as the classifying agent like for instance, whether the process uses lasers, extrusion or printer technology, etc., while others club the processes together on the basis of the type of raw material used. 'Method of bonding' such as chemical bond, sintering and gluing, was used by Kulkarni et al. (2000) to categorize layered manufacturing technologies. However, the classification used by the ASTM F42 committee, is universal and applicable globally. According to Gibson et al. (2015) and Monzon et al. (2014), AM is split in to 7 areas by the committee; vat photopolymerization (process that cures a liquid photopolymer contained in a vat by providing energy at specific locations of a cross-section), material jetting (process that uses ink-jet for printing), binder jetting (process which prints a binder in to a powder bed to form a part cross-section), material extrusion (process that makes a part by extruding material through a nozzle), powder bed fusion (process that uses an energy source like a scanning laser to selectively process a container filled with powder), sheet lamination (process that deposits material in form of layers), and directed energy deposition (process that uses a single deposition device to simultaneously deposit material and provide energy to process the material). The associated AM processes for each of the 7 classes are numerous; but, Huang et al. (2015) provided a comprehensive overview of all the concerned classes along with their popular associated AM processes, materials used in those machines and their famous manufacturers as depicted in Table 2.1.

Process Category	**AM Process**	**Material**	**Manufacturer**	**Machine Examples**
Vat Photopolymerization	SLA	UV Curable Resins	Asiga	Freeform Pico
			3D Systems	iPro
				Projet6000/7000
			EnvisionTEC	Perfactory
			Rapidshare	S Series
		Waxes	DWS	DigitalWAX
		Ceramics	Lithoz	CeraFab 7500
Material Jetting	MJM	UV Curable Resins	3D Systems	Projet 3500 HD/3510/5000/5500
			Stratasys	Objet
		Waxes	Solidscape	3Z
Binder Jetting	3DP	Composites	3D Systems	Z-Corp
		Polymers,	Voxeljet	VX Series

		Ceramics, Sand		
		Metals	ExOne	M-Flex
Material Extrusion	FDM	Thermoplastics	Stratasys	Dimension
				Fortus
				Mojo
				uPrint
			MakerBot	Replicator
			RepRap	RepRap
			Delta Micro Factory Corporation	UP
			Beijing Tiertime	Inspire A450
		Waxes	Essential Dynamics	Imagine
	APF	Thermoplastics	Arburg	Freeformer
Powder Bed Fusion	SLS	Thermoplastics	EOS	EOS P
			Blueprinter	SHS
			3D Systems	sPro
	SLM	Metals	EOS	EOSINT M
			SLM Solutions	SLM
			3Geometry	DSM
			Concept Laser	LaserCusing
			3D Systems	ProX
			Realizer	SLM
			Renishaw	AM250
	EBM	Metals	Arcam	Arcam A2
			Sciaky	DM
Sheet Lamination	LOM	Paper	Mcor Technologies	Matrix 300+
		Thermoplastics	Solido	SD300Pro
Directed Energy Deposition	LMD / LENS	Metals	Optomec	LENS 450
			Irepa Laser	EasyCLAD
	EBAM	Metals	Sciaky	VX-110

Table 2.1 AM Processes, Materials and Manufacturers –Modified from Huang et al. (2015)

The capability of AM to manufacture anything has brought about a paradigm shift from DFM to Manufacturing for Design (MFD). Yang and Zhao (2015) split the level of complexity achieved by AM into four domains: ‘shape complexity’, i.e., it is possible to manufacture any shape reducing the lot size to a single piece and leading to opportunities for shape optimization; ‘hierarchical complexity’ wherein features at a one size scale can have smaller features added to them; ‘material complexity’ which can allow the user to work on one layer at a time providing a window to work with various materials at the same time; and ‘functional complexity', i.e., when parts are built, the interior of parts can be made accessible to integrate further multiple designs. The benefits of such capabilities are numerous including shorter time to market, achieving individualization of products, enjoying tool free manufacturing with on-demand and de-centralized production, having intricate features, gaining luxury of early market positioning as the development is faster, reducing production costs, and thriving product customization (Lindemann et al., 2012; Mieritz et al., 2008).

Additionally, whenever manufacturing processes and the forecasted developments are studied, engineers and designers, keeping in view the capabilities of AM, are on a constant look out to optimize the process chains. Ghazi (2012) defined AM process chain as any manufacturing process route that involves at least one AM process. The end part can be a tool, a die or a prototype. Usually AM processes are not used alone, and some secondary processes are used for finishing like grinding, polishing, etc. Lazer polishing was used by Lamikiz et al. (2007) to enhance the surface finish of a part produced by SLS. Similarly, Galantucci et al. (2009) utilized chemical post treatment on FDM parts made of Acrylonitrile Butadiene Styrene (ABS).

Moreover, in a hybrid fashion, i.e., to use a combination of AM and TM processes, cost and time for the manufacture of part can be greatly improved. For example, Das et al. (1999) used SLS/HIP (Hot Isostatic Pressing) to manufacture a titanium sidewinder missile guidance section housing. Similarly, Ilyas et al. (2010) utilized a hybrid AM process chain which consisted of first an indirect SLS process to build the mould. Then, High Speed Machining (HSM) was used as a primary operation, and finally Electron Discharge Machining (EDM) was utilized for grinding and polishing of the end-product. The different possible process chains for AM process are shown in Figure 2.5.

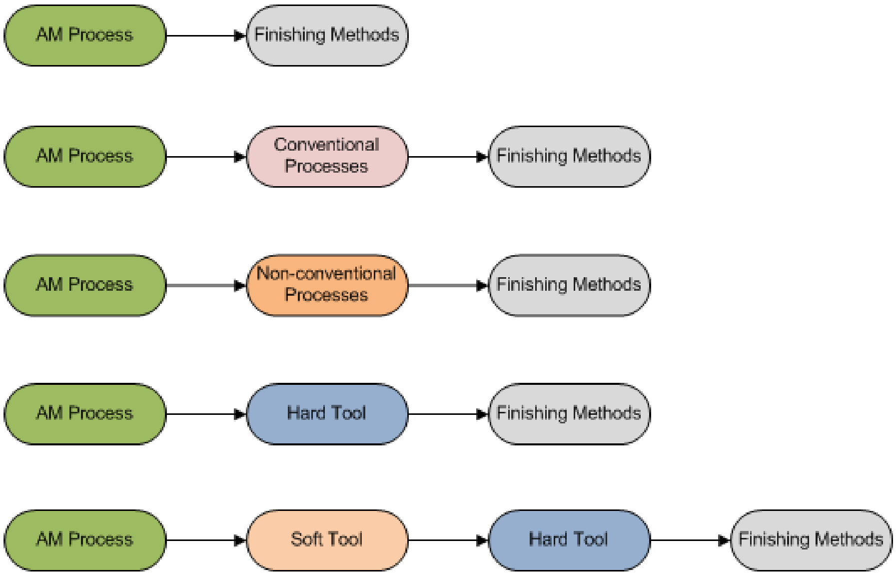


Figure 2.5. Types of AM Process Chains (Reproduced from Ghazi, p-21).

Furthermore, it is also necessary to understand how products suitable for AM can be identified. Table 2.2 shows a 'one-stop' solution adopted from Klahn et al. (2014). The solution discusses four selection criteria to select components for a design or re-design (if required) to fully exploit the geometric freedom of AM. For instance, if the objective is to identify assemblies or group of parts which can be re-designed in to one single part, 'functions integration' should be the selection criterion as it addresses research questions like; can the assembly time be reduced? can the product size be altered in terms of volume while achieving the same function? etc. Similarly, if the research question involves topology optimization (a method to generate optimized designs in the form of material distributions in 2D/3D space), the selection criterion 'weight and material cost savings' should be used. The typical candidates for each of the criteria are also listed.

Having discussed the forecasts related to AM market, AM process chains and the criteria to choose AM products, the issues pertaining to usage of AM technology needs attention, too. Having unlimited potential for AM does not guarantee having unlimited capability. The materials in today's market are evolving with each passing day and the issue of the best material-manufacturing process mapping remains a most researched problem. Therefore, the designers working in the AM industry have to not only concentrate on the types of constraints involved in procedures such as Computer Aided Design (CAD) and the digitization of its ideas (Huang et al., 2015), discretization (digital and physical) of the parts to be produced, assessing capabilities of AM machines, and processing of materials to gauge the impact on properties, but also cater for new challenges and requirements associated with metrology and quality control, maintenance, repair, lack of generic interdependency between materials and processes, limitation in material selection, longer design cycle than manufacturing cycle, surface finishing issues and post-processing requirements (Cozmei and Caloian, 2012; Vaezi et al., 2012). Similarly, AM generally lacks dimensional accuracy, close tolerances, invites problems related to support design and removal (in techniques like SLS), incorporates a high build time if the component size is large, is affected by the lack of AM standards and data formats, requires specialized labour, and has recently invited the consideration of environmental factors in the design phase (Atzeni et al., 2010; Monzon et al., 2014; Yang and Zhao, 2015).

Selection Criteria	Research Questions			Objective	Typical Candidates
Functions Integration	Can functions or sub-parts be merged into one component?	Can the number of interfaces and/or joints be minimized?	Can the product be reduced in size or volume while achieving the same function?	Identify assemblies (group of parts) which can be re-designed in to one single part	Single-function assemblies and complex assemblies made of single function parts
Customization	How many design variations are expected?	Can this product be separated/assembled in core and customizable add-ons?	How much variation between design versions?	To produce products that become assembly of standard components and customized add-ons	Consumer products
Weight and Material Costs Savings	Can weight-reduction improve performance of the components?	Can material volume be reduced to save money at equal or superior performance?	Can topology be optimized?	To selectively place material in locations required by the function to increase the geometric complexity of the component	Complex load bearing parts
Operation Efficiency	How could the product operate more efficiently? How can losses be reduced during operation? How can performance be improved during operation?	How can mass or energy transport be maximized?	Can running costs be lowered?	Improve the efficiency of product in operation	Components involved in production

Table 2.2 Guidelines to identify products suitable for AM (Klahn et al., 2014)

2.1.1 Conclusion

This section presented an overview of AM technology with focus on the market share attained by AM and its projected forecasts. It also discussed the most popular and common types of AM processes, machines and materials with respect to the classification proposed by the ASTM F42 committee. The different types of AM process chains were discussed, too, to invite one side of the concept of integrated product-process development which caters for how and when to use AM technology with respect to its capabilities. Some issues related to AM were discussed as well. Moreover, as the stakeholders in AM industry related to part manufacture are not altering the design completely in the 'design phase' thereby resulting in an increase in the costs incurred both due to manufacturability and production time, it is highly important to address the relationship between manufacturing constraints, customer requirements and design guidelines so that the overall cost including assembly and logistics is minimized. The state-of-the-art pertaining to this issue is presented in Section 2.2.

2.2 Integrated Product-Process Design (IPPD) and Design Criteria for MPS Problem

Design and Manufacturing are two important aspects of the product development cycle. In order to decrease the costs incurred due to the manufacturability of a part, there should be freedom to alter the design in the design phase. However, according to the current practices in industries, a major gap exists between design and its effect on manufacturability which has led to increase in both the production cost and time. Moreover, it is important in product life cycle that the designed products should be able to get manufactured by the machines and labour in a facility at the lowest cost. Wright (1998) depicted the process flow in a product development process by highlighting the important constraints and considerations as feedback arrows as shown in figure below:

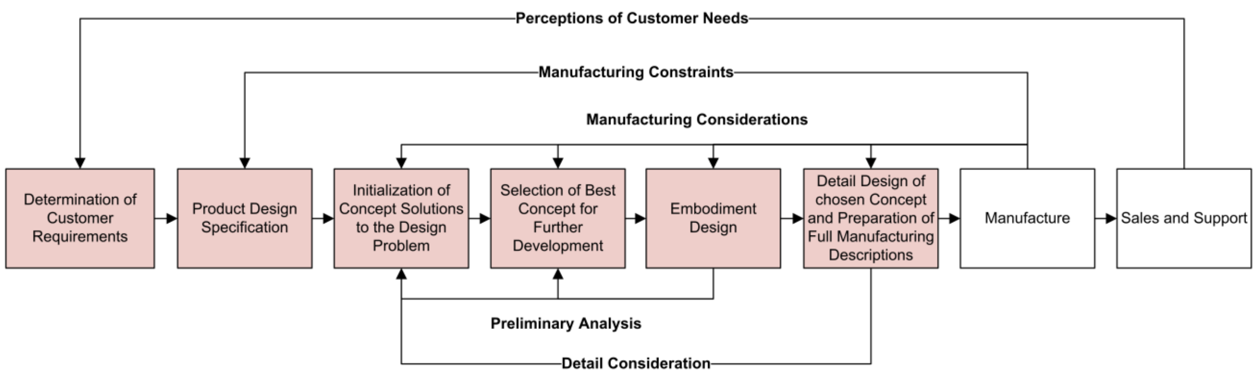


Figure 2.6. Product Development Process (Reproduced from Wright, 1998)

The boxes shaded above are concerned with the design stages of the overall product development process. The concept of DFM was developed under the same notion to address the relationship between manufacturing constraints, guidelines and customer needs by providing some generic guidelines so that the overall cost including assembly and logistics is minimized (Gibson et al., 2015). But this approach has long been in practice and with new emerging technology paradigms such as cloud manufacturing and AM, companies and individuals are on a constant strive to fulfil the targets of TQCSEK (i.e., fastest Time-to-Market, highest Quality, lowest Cost, best Service, cleanest Environment and high Knowledge) (Zhang et al., 2014). This also means that the arrows on the lower side of Figure 2.4, i.e., preliminary analysis and detail consideration, are imperative to product definition, while the arrows on the upper side including manufacturing considerations and constraints, are important for process plan definition, especially for the new technologies.

Farag (2014) re-emphasized the design phase by proposing that three factors should be considered in designing a component; manufacturing processes, material properties, and function & consumer requirements (see Figure 2.7). As these factors are interlinked, the optimum design is a trade-off between many conflicting conditions such as economic factors, functional requirements, safety concerns, environmental impact, etc. Furthermore, this idea conforms to the requirements of CE which helps in increased productivity and product quality (Quan and Jianmin, 2006). Also, the traditional sequential flow or 'Waterfall model' is replaced in such a case with 'integrated development method' which follows an iterative procedure in a cyclic manner by employing decision making and evolutionary techniques (Balaji and Murugaiyan, 2012; Royce and Winston, 1970).

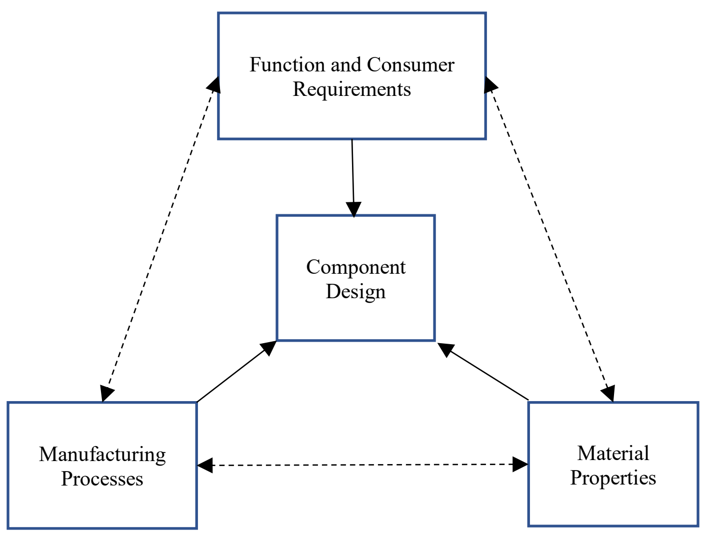


Figure 2.7. Factors to be considered in component design (Reproduced from Farag, p-150)

This further invites the concept of IPPD. In the context of TM, Tichkiewitch and Veron (1998) explained it with reference to a process chain of forging-machining and suggested that whenever a part is designed, it is split into a frame view (built with skin features and representations of functional surfaces) and a geometric view (built with theoretic surfaces and supports CAD representation). The frame view is optimized for forging while for the later process of machining, process plans are generated to transfer geometric features to machining features for a geometric view. Thibault et al. (2008) also used an expert system and group technology for product-process integration in the forging domain. They generated the product-process requirements by defining process plan schemas. Moreover, Skander et al. (2008) proposed a knowledge synthesis method which integrated manufacturing constraints in the product definition stage by utilizing skin and skeleton features for the design part. Earlier in 2003, Roucoules and Skander had provided an approach for both analysis and synthesis in the product development process. For analysis portion, they considered DFM and manufacturing process selection, while for synthesis, manufacturing constraints were considered as a loop between product modeling phase and manufacturing phase. Furthermore, Bernard et al. (2003) used the concept of a 'quotation' by utilizing knowledge-based engineering approach to integrate economic criteria in design and production decisions. They simulated process parameters to validate the CAD definitions for a casted part.

However, for the context of AM in IPPD, Klahn et al. (2015) suggested two design strategies for AM; 'manufacturing-driven design strategy' and 'function-driven design strategy'. The former strategy can be used to mass customize a part by maintaining a conventional design and following design rules of other manufacturing technologies, while the latter strategy improves the function of a product as done by Klahn et al. (2014) for a medical device that was used in shockwave therapy. RP itself is a great example of utilizing AM's process advantages by considering a part which is designed for conventional production. Moreover, manufacturing driven design strategy is largely used to mass customize a product in series production as identified by Berger (2013) for additive manufactured dental implants. The strategy is also used in direct production of thermoplastic parts via materials such as composites (Cerneels et al., 2013). Boivie et al. (2011) also streamlined the production sequence of a hybrid manufacturing cell by integrating AM with Computer Numeric Control (CNC) milling. They selected Marlok C1650 tool steel for the associated cell. Moreover, Ponche et al. (2014) not only optimized the design in a three-step process; determine part orientation, optimize topology of the part, and optimize manufacturing paths, but also catered for the manufacturing constraints and considerations. D'Antonio et al. (2016) also integrated DfAM with Manufacturing Execution System (MES) to analyze and synthesize product and process data. They extended the model of Rosen (2007) who after planning a manufacturing process, performed simulations to check whether the functional requirements were satisfied. An approach was also proposed for the modeling of process chains for AM to support the CE along with process selection and DFM in early design stages (Thompson et al., 2016). Zaman et al. (2017) proposed a generic methodology to suggest appropriate manufacturing technology (additive or traditional) keeping in view the interaction between product and process data. Finally, Yazdi et al. (2016) proposed an integrated approach to apply CE perspective to AM technology by using DFM-skin and skeleton for process modeling in early stages of product development cycle and suggesting an interface model to support both the design and manufacturing attributes for a product.

Specifically, in relation to process parameters of AM and keeping in view the above-mentioned studies, the paragraphs to follow will attempt to highlight the common design criteria used in literature with respect to IPPD and DFM/DfAM/DFX.

2.2.1 Design Criteria: Function

'Functional requirements' (see Figure 2.5) govern the basis of any selection strategy. In reference to MPS problem, the achievement of such requirements can be thought of as a solution that involves execution of a 'manufacturing task' by sending the output involving a certain feedback to the designer for refinement in design features. The task-based selection should also carefully cater for the 'requirements' and the 'attributes', where the former can be design-related (specifying function of component and the design information on the engineering drawing), production-related (requiring details for the shop floor like production rate and batch size), and processing-related (explaining process-specific issues), while the latter refer to the characteristics of the process (e.g. capital cost), material (e.g. performance indices) and design (e.g. geometry) (Shercliff and Lovatt, 2001). Ashby (2005) further suggested the use of 'material indices' to find the performance of a component by evaluating a performance equation. Such an equation addresses the function requirements, objectives and constraints by evaluating group of material properties referred to as the material indices. For example, if the performance of a beam is measured by its stiffness, the performance equation will contain only one property, i.e., elastic modulus, E, and this will also constitute as the material index for the problem. The performance equation can contain one or more material indices which are vital to the optimal selection of materials. Moreover, the material indices are independent of the design of the component, thereby giving them an element of generality.

Considering the material properties and manufacturing processes, Ashby et al. (2012) discussed the material and process attributes. The menu of engineering materials includes metals (e.g. steels, cast irons, Cu-alloys, Ti-alloys, etc.), polymers (e.g. polyethylene, polypropylene, nylons, polyesters, etc.), ceramics (aluminas, silicon carbides, etc.), elastomers (isoprene, neoprene, natural rubber, silicones, etc.), glasses (soda glass, silica glass, glass-ceramics, etc.) and hybrids (sandwiches, segmented structures, lattices, foams, etc.). Figure 2.8 suggests an example hierarchical organization for metals and the associated attributes.

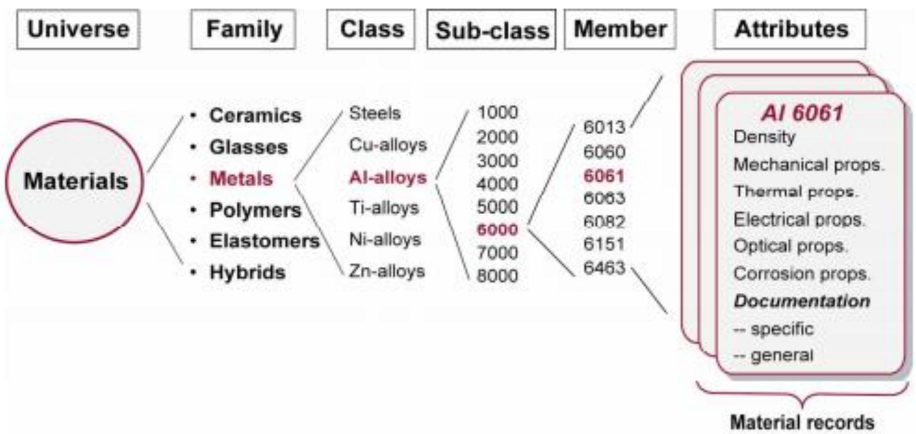


Figure 2.8. Hierarchical structure for material classification (Ashby, p-3)

Similarly, for process attributes, Ashby et al. (2012) classified the manufacturing processes into three families; shaping, joining and surface treatment. Each of these families were then further broken up into attributes. One such classification for shaping family is shown in Figure 2.9.

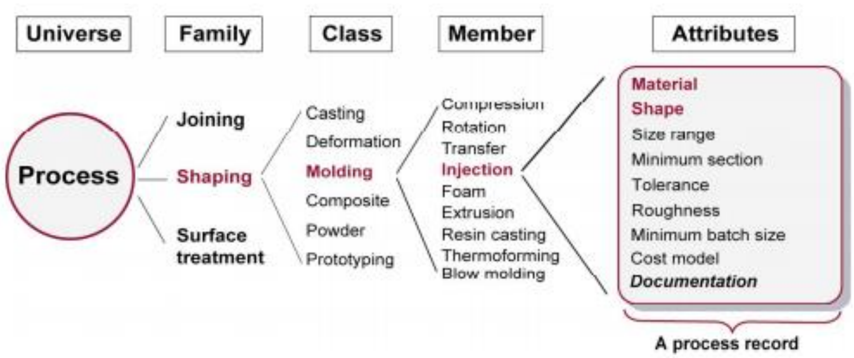


Figure 2.9. Hierarchical structure for process classification (Ashby, p-3)

Moreover, Tang et al. (2014) classified the design methods subject to function optimization in to three groups; macro (structural optimization), meso (use of cellular structures) and micro (control of fabrication parameters). Tang et al. (2011) performed designs of material selection and structural optimization simultaneously with special focus on size and shape optimization. Ponche et al. (2012) suggested that manufacturing strategies influence part geometry, material characteristics and the final part quality. To cater for these factors, they proposed a global methodology which determined the most suitable manufacturing plan for a part geometry by considering the functionality and manufacturability. But with respect to MPS, topology optimization has recently gained more attention especially with reference to material distribution optimization in a given design space by emerging technologies such as AM. Few popular techniques used in literature include ground structure method (Bendsoe et al., 1994; Dorn et al., 1964), homogenization method (Bendsoe and Kikuchi, 1988), Solid Isotropic Material with Penalization (SIMP) method (Rozvany et al., 1992), evolution method (Xie and Steven, 1993; Young et al., 1999), and genetic method (Chen et al., 2009; Wang and Tai, 2005). The use of cellular structures, especially lattices and honey combs has also helped in material and performance optimization for MPS. Wang and Rosen (2002) used parametric modeling to create truss structures to enhance the mechanical and dynamic properties of a part. Chen (2007) also mapped meostructures into the design phase to generate internal structures. As far as enhancement of fabrication parameters are concerned, the recent discovery of Functionally Graded Materials (FGMs) has helped to change the micro-structure of one or many different compositions in the design space (Muller et al., 2013). AM and other emerging technologies have frequently used FGMs for MPS (Khoda and Kok, 2013; Podshivalov et al., 2013).

Vayre et al. (2012) also improved the part design in AM by proposing a new methodology and verified it on a sample test part. A numerical chain based method was similarly proposed by Ponche et al. (2014) who explored the optimized geometry while considering manufacturing process characteristics simultaneously. They tested the method on turbine blades with an objective of minimizing their mass and making sure that the mechanical strength remained intact. Moreover, Munguia et al. (2008) suggested the optimal build orientation. For instance, in SLS, the Z-axis must be used as a reference for improving the tensile strength whereas, if elongation properties need to be made better, XY direction should be chosen.

2.2.2 DFM, DfAM and Design for 'X' (DFX)

The 'X' in DFX stands for manufacturability, recyclability, inspectability, etc. The DTM methods referred to in the 'Introduction' section broadly represent DFX and include elements like DFM, DFMA, Design for Disassembly (DFD) and Design for Assembly (DFA), referred to as the general or conventional DFX. Yang and Zhao (2015) proposed fourteen guidelines for general DFX which are summarized in Table 2.3.

Point	Description
1	Design simply complying with functional requirements
2	Minimize the part count
3	Integrate parts
4	Separate working components into modular sub-assemblies
5	Minimize material types in an assembly
6	Standardize components
7	Create multi-functional parts
8	Design for the ease of fabrication
9	Design for the ease of assembly (position, handling, joining and access)
10	Avoid using laminates
11	Avoid surface demands on components
12	Avoid secondary operations
13	Eliminate adjustments
14	Use ferromagnetic materials

Table 2.3. General guidelines for conventional DFX (Yang and Zhao, p-331,332).

Moreover, with the passage of time, it was realized that the guidelines above well covered the function and cost perspective but issues such as recyclability and environmental concerns needed attention, too. Various researchers have since worked on areas such as design for environment, design for recyclability, design for life-cycle, etc., in this regard (Kuo et al., 2001).

It is well known that AM has the freedom to virtually manufacture anything. So, the general DFX guidelines have been studied by various authors in literature and modified to suite AM needs. Figure 2.10 shows the relationship between DFM, DFA, DFMA and DFD. It also displays how

DfAM helps in removing the tradeoffs (keeping in view the guidelines in Table 2.3) for two parameters; design complexity and manufacturing constraints. This is evident by the guidelines 8 and 9 lying on the periphery. DfAM displayed an advantage when it deactivated this tradeoff by fundamentally manufacturing anything without getting involved in the assembly constraints. There is no need of having draft angles, wall thicknesses can be varied throughout the part, sharp corners can be obtained depending on part geometry, and large part designs can be split, built in sections and then bonded together, thereby, eliminating size limitations[3].

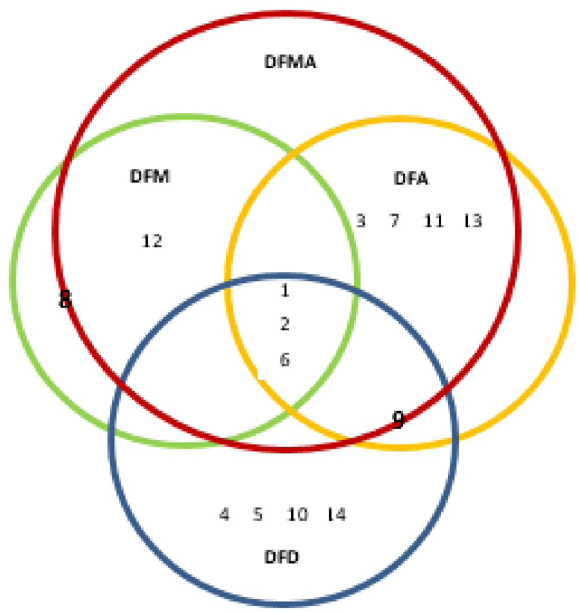


Figure 2.10. Relationship between DFM, DFD, DFMA and DFA (Reproduced from Yang and Zhao, p-334).

Kannan (2013) emphasized on the fact that although the design rules might appear simple for AM but verifying all of them manually can be tiresome and lengthy. Here DFX for AM comes in to play and a variety of CAD formats such as Pro/E, CATIA, SolidWorks, STEP, etc. can be used. The DFX for AM will help in reducing design iterations, manufacturing lead time, multiple trials and finally the cost of manufacturing. The proposed DFX rules for AM are listed in Table 2.4.

[3] https://www.stratasysdirect.com/wp-content/uploads/2015/07/fdm-basics.pdf

Sr. No.	Rules and Checks	Description
1	Maximum Part Size Check	Compares the size of part with maximum allowable limit and shows failure if limit is exceeded
2	Minimum Wall Thickness Check	Examines the wall thickness and identifies regions where thickness is lesser than allowable minimum thickness
3	Faces Requiring Support Rule	Recognizes the faces that require support
4	Minimum Thickness of Faces Requiring Support Rule	Compares thicknesses of faces requiring support with minimum allowable thickness
5	Minimum feature size Rule	Compares the feature sizes with minimum allowable feature size
6	Recommended Rib Parameters Check	Recognizes ribs and compares the ratios of (a) rib-base thickness to nominal wall thickness and (b) rib height to normal wall thickness with that of maximum allowable ratio
7	Rib Reinforcement Check	Compares the ratio of (a) rib area to nominal wall thickness and (b) rib width to nominal wall thickness with that of maximum allowable ratio
8	Boss Inner Diameter (ID) to Outer Diameter (OD) Ratio Check	Recognizes bosses and compares ratio of ID to OD with that of allowable minimum ratio
9	Boss Height to OD Ratio Check	Compares the ratio of boss height to OD with that of maximum allowable ratio
10	Minimum Hole Diameter to Thickness or Depth Ratio Check	Recognizes holes and compares actual diameter to thickness (depth) ratio with that of allowable minimum ratio
11	Knife Edge Check	Recognizes knife edges
12	Recommended Corner Radius Check	Recognizes fillets and compares actual diameter with minimum allowable radius
13	XYZ Slice Dimensions Check	Checks whether all XY and Z dimensions are exact multiples of required resolution.

Table 2.4. DFX rules for AM (Kannan, p. 7-9)

Adam and Zimmer (2014) further reinforced the idea of design freedom by AM by deriving process independent design rules. They divided the standard shapes of parts into three groups; basic elements (elementary geometrical shapes like cylinders), element transitions (areas where basic elements interact with each other like joints), and aggregated structures (combination of two or more basic elements and element transitions like overhangs). The design rules developed provided the suitable ranges in which the attributes can be adjusted to achieve optimal quality. Vayre et al. (2012) also improved the part design by proposing a new methodology and verified it on a sample test part. A structured catalogue containing basic design guidelines was issued by Kranz et al. (2015) for Laser AM (LAM) of TiAl6V4. Seepersad et al. (2012) manufactured plastic components using SLS and presented a set of design guidelines for better manufacturability of parts. Finally, Zaman et al., 2018b suggested a design-oriented framework for MPS in AM to structure design knowledge pertaining to each stage of design process; conceptual, embodiment and detail designs.

2.2.2.1 Design of Experiments – Taguchi's method

Section 2.2.2 introduced the design rules for part and process optimization. But to identify the engineering and process parameters based on the design features and functional requirements, a yet another avenue of application exists, i.e., DOE. In AM, several factors need to be considered prior to manufacturing such as layer thickness, type of powder used, quality of printer head, orientation and location of parts, shrinkage, and binder setting saturation value. Each of the factors mentioned affect the quality and the build time in one way or the other. Moreover, it has been known with experience and observations that although most controllable factors have some effect, but the quality is dominated by few primary control factors (Yao and Tseng, 2002; Stopp et al., 2008) like location of parts, layer thickness, and setting values of shrinkage, to name a few.

Full factorial method is generally used as a standard approach for experimental design, but the method is only suitable if the factors being investigated are few (usually not more than three). But if the factors are more and the number of times an experiment is conducted needs reduction, Taguchi technique has been quite successful (Roy, 2001; Hsu and Lai, 2011). It is based on mixed levels, highly fractional factorial designs, and other orthogonal designs. With the application of Analysis of Variance (ANOVA) on Taguchi method, the influence of each factor on the common goal can be attained. And by Signal-to-Noise (S/N) ratio, the degree of the influence of different factor levels and the noise factors that affect the experimental result, can be determined. In other words, S/N ratio is an objective index to measure quality stability. Taguchi's approach, therefore, not only saves time and cost but also provides simple, efficient and systematic methodology for the optimization of near optimum design parameters with only a few well-defined experimental runs (Prasad et al., 2005).

In AM, Taguchi's method has been used with much effect. Rahmati et al. (2007) applied Taguchi's DOE for the determination of optimum condition for dimensional accuracy when creating wax models by room temperature vulcanization (RTV) silicon rubber moulding SLA pattern. Wang et al. (2007) analysed factors like ultimate tensile strength, dimensional accuracy and surface roughness in FDM process via integration of Taguchi's DOE and Gray relational analysis. Speed, accuracy and strength of green parts were further analysed by Hsu and Lai (2010) to reduce the dimensional accuracy error (X, Y and Z directions) in 3D systems. Moreover, Onuh and Hon (1998) carried out experiments to statistically determine the build parameters to improve the surface finish of SLA parts alongside Anitha et al. (2001) who did the same for FDM process. With respect to metal AM, Chhabra and Singh (2012) studied experimentally the effect of process parameters on surface roughness of castings obtained by ZCast direct metal casting process. Finally, Lakshmi and Arumaikkannu (2014) and Naiju et al. (2012) studied the SLS process and analysed the surface finish and fatigue reliability, respectively.

2.2.3 Design Criteria: Cost

Considering the design criteria of 'Cost', different cost models were suggested by authors in literature with respect to MPS problem and how they affect the design phase. However, before discussing them, it is important to get a picture of how cost per part changes with the number of parts for each of AM and TM technologies. As 3D printing is often interchangeably used as a term for AM, Deloitte (2015) provided a breakeven analysis of 3D printing and conventional manufacturing (interchangeably used for TM) as shown in Figure 2.11. For the case of TM, the cost of producing a unit is initially high but falls as more number of units are manufactured. This also implies that 'mass production' is an important aspect of TM. On the other hand, the cost of AM is not that high because the cost of tools is much lower. The breakeven point is where the two curves meet. Currently, TM offers cost advantage when the production volumes are high. AM, however, is attractive even for smaller volumes when it gives the capability to produce more complex designs, have a rapid market launch (requirement of fewer tools provides savings on development time) and provide a decrease in waste. Moreover, for AM, the disadvantage lies in the cost of mass production which is very high due to limited range of printable materials (especially metal powders, polymers and ceramics) and limitations on the size of parts that can be printed (Deloitte, 2015).

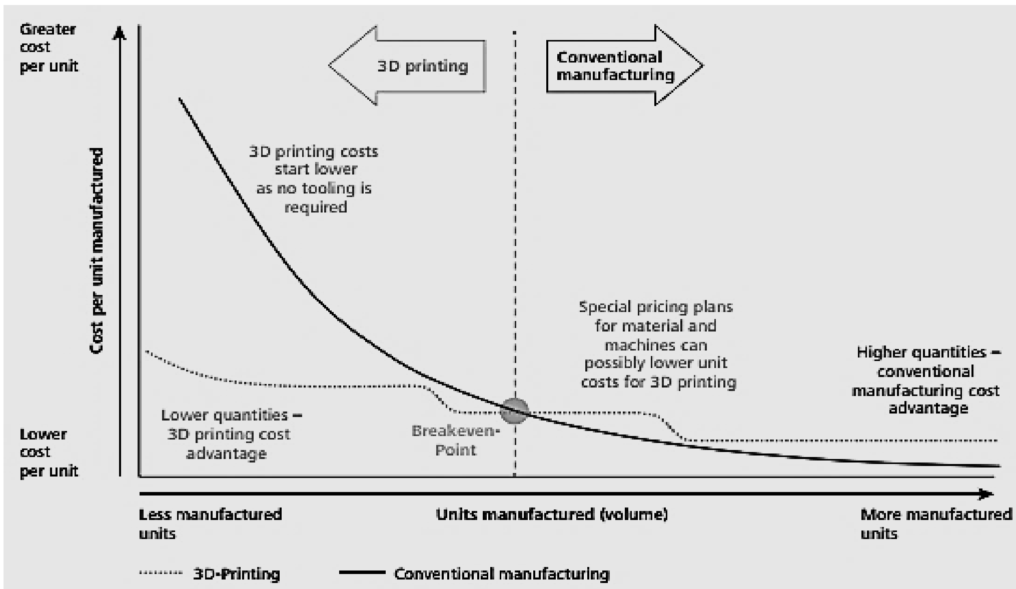


Figure 2.11. Breakeven analysis of conventional manufacturing and 3D printing (Deloitte, p-18)

Hopkinson and Dickens (2003) had a cost comparison of SLA, Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) with Injection Molding (IM) to fabricate a polycarbonate lever. Tool cost was a significant factor for IM and the cost per part dropped rapidly from 16 to 0.23 euros for an increase in batch size from 1,710 to 20,000 pieces. The cost per part however, remained the same for all other AM processes. Ruffo et al. (2006) improved the model proposed by Hopkinson and Dickens in 2003 (generated constant line for SLS) by manufacturing the same lever with SLS. They generated a new curve (applicable to all AM) which showed a deflection for low production volumes (for batch size of less than 1,500 parts) rather than being constant. They also used activity-based model approach with an assumption that the SLS machine had 57% utilization, i.e., it worked 100 hours per week for 50 weeks per year. Their curve changed for three conditions viz. filling a line (a new row is used in the x-direction for the addition of a part), filling a layer (a new vertical layer is added for the addition of a part) and filling a bed (a new bed is started for the addition of a part). Each of these conditions tend to increase the manufacturing time and indirect costs in production. For higher number of parts, the curve stabilized even more because the indirect cost was split on the associated large volume of parts. Moreover, the authors emphasized that initial transition and the final stabilized value on the curve depended on 'part size' and 'packing ratio' where the former parameter provided quick filling of machine beds and layers if the part was big, hence splitting the additional cost between fewer parts, while the latter parameter affected both build time and material waste. Therefore, optimizing build chamber by maximizing the area is essential in reducing costs as incomplete use of the available chamber will lead to inefficient machine operation. Baumers et al. (2013) proposed a combined bottom-right-left and centre-of-mass placement algorithm to demonstrate that process efficiency is positively impacted if utilization of available machine capacity is enhanced. Other placement heuristic approaches have also been used in literature such as geometrical translation implementation (Egeblad et al., 2009) and no-fit polygon (Dowsland et al., 1998).

Atzeni et al. (2010) provided a near similar cost comparison to that of Hopkinson and Dickens (2003) for IM and SLS using EOS Polyamide PA2210 FR material. By correlation analysis, mould cost was the only significant parameter for IM as a deviation of ± 20 percent in mould cost resulted in only ± 19 percent in total cost per part up to 100,000 pieces. For SLS, machine cost was found to be twice as dominant as material cost and a change of ± 20 percent in the machine and material costs resulted in 6 to 18 percent in total cost per part. In all, a comprehensive analysis was provided by the authors on how different cost parameters change the position of breakeven point. They concluded that AM is appropriate for medium lot productions even for mass customization products. Table 2.5 and Figure 2.12 show the effect of machine and material cost on both total cost per assembly and breakeven point.

Effect of most dominating parameters change on total cost per assembly for RM*									
	Total Cost [€ (%)]								
Machine (per h)	-20%	-20%	-20%	Ref.	Ref.	Ref.	+20%	+20%	+20%
Material (per kg)	-20%	Ref.	+20%	-20%	Ref.	+20%	-20%	Ref.	+20%
	0.972 (-17.8%)	1.044 (-11.7%)	1.116 (-5.7%)	1.111 (-6.1%)	1.183	1.255 (+6.1%)	1.25 (+5.7%)	1.322 (+11.7%)	1.394 (+17.8%)

Table 2.5. Effect of most significant parameters change on total cost per assembly for AM (Reproduced from Atzeni et al., p-316)

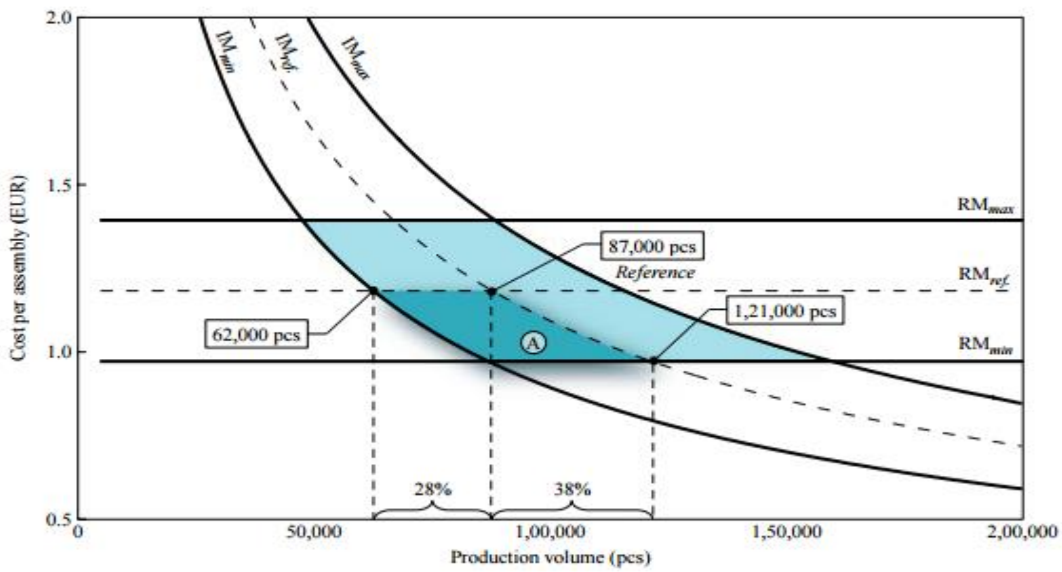


Figure 2.12. Effect of most significant cost parameters change on breakeven point (Atzeni et al., p-316)

Lindemann et al. (2012) also studied various cost drivers such as material costs, machine investment costs, building rate and utilization rate to analyze product life cycle costs of AM wherein a part was manufactured using 316L Stainless Steel (SS) material. It was found that the largest contributor of building costs was 'machine costs' followed by 'material costs' and 'labor costs'. Lattice structures were used by Gorny et al. (2011) to decrease material volume and subsequently the cost of the build. Also, skilled labor is required to place the parts in the building chamber. Furthermore, cost comparison of a landing gear structure of aluminum was made by Atzeni and Salmi (2012) by two manufacturing processes; High Pressure Die Casting (HPDC) and

SLS. It was concluded from their study that for production runs less than 42, SLS was more effective than HPDC. Munguia et al. (2008) suggested that selection of layer thickness contributes to both cost and quality. For example, layer thickness of 0.1 mm for SLS and (20-60) mm for DMLS. In addition, designing the optimal support structure helps to reduce material usage and corresponding costs. Last, Allen (2006) compared AM with TM (subtractive) for aero engine parts and proposed to increase material deposition efficiencies and decrease material costs to decrease final cost per part for AM.

2.2.4 Design Criteria: Environment

Environment is the third design criterion that has been attempted to be discussed in this review. This criterion has recently taken a lot of importance and Environmentally Responsible Manufacturing (ERM) is continuously evolving to eliminate all waste streams associated with the design, manufacture and disposal of materials and finished/semi-finished products (Sroufe et al., 2000). As the environmental criterion is also the attribute of a product, it can be translated into metric form and can be used to develop the product in early stages of design (Kuo. et al., 2001). Moreover, 'energy efficiency' plays a vital role in reducing the environmental impact. As per the report by IEA (2016), energy efficiency improvements have been on the rise with IEA countries[4] avoiding 1.2 billion tonnes of CO_2 ($MtCO_2$) in 2014 and 10.2 $GtCO_2$ over the period since 1990. Since, the UN Framework Convention on Climate Change (UNFCCC) negotiations in Paris in late 2015, the environmental returns from energy efficiency are gaining more attention. Avoiding the combustion of fossil fuels at relatively little cost will help energy efficiency to play a critical role in decarbonization efforts.

Huang et al. (2013) provided a comparison of energy use and environmental impact for AM processes (SLA, SLS and FDM) and TM techniques (casting, flexible machining and clean machining). The materials used in each of SLA, SLS and FDM were SL 5170 epoxy resin, polymer and ABS, respectively. The table below shows the results which are very promising in case of AM processes.

[4] IEA countries include all OECD countries except Chile, Iceland, Israel, Mexico and Slovenia.

Process	Energy use (kg CO2 per component)	Water usage (kg per component)	Landfill waste (kg)	Virgin material use (kg per component)	Hazardous waste (kg per component)
Casting	1.9	0	N/A	2	N/A
Flexible Machining	2.4	0.08	1.512 (waste can be recycled)	2 (from casting)	0.0064
Clean Machining	N/A	0.15	N/A	N/A	N/A
AM	13.15	0	0	0.65	0

Table 2.6. Comparison of energy use and environmental impact of AM and TM techniques (Reproduced from Huang et al., p-1198).

Telenko and Seepersad (2012) provided an energy efficiency comparison of SLS and IM for nylon parts. They divided their experiment into two phases, one for small build, i.e., 50 parts and second for full build, i.e., 150 parts. As mould is an important part of IM, recycled steel mould was used. They analysed processes like build preheat, part manufacture, recycled steel mould production and nylon production. Having a consolidated analysis of all processes revealed that for small build, SLS consumed less energy compared to IM. However, for the full build, SLS consumed more energy compared to IM.

Considering the comparison between different AM processes for environment and energy, Mognol et al. (2006) discussed the effect of 'manufacturing time' on the electrical energy consumption of Thermojet, FDM and SLS. They concluded that for Thermojet and SLS, the height of the part must be minimized while for FDM, the volume of support must be minimized to decrease the manufacturing time. If such measures are taken, there is an expected decrease in electrical energy consumption by 45% for Thermojet, 61% for FDM and 43% for SLS. Xu et al. (2015) also conducted experiments on the binder jetting system to demonstrate the correlation between part geometries and energy consumption during production. Build time was considered the most important factor since energy consumption is directly dependent on the build time.

2.2.5 Conclusion

This section highlighted the importance of considering product and process parameters in early stages of design. Three design criteria; function, cost and environment were studied in reference to MPS problem with focus on AM. The design guidelines with reference to AM were also reviewed and important factors were highlighted. Taguchi's DOE was also studied with respect to AM to get insight into process parameters' optimization.

2.3 Material and Manufacturing Process Selection Strategies

In section 2.2, requirements related to how a part could be manufactured were generated from the mash-up between DFM / DfAM / DFX guidelines and the design criteria. These requirements must be linked with the MPS selection strategies. Therefore, in this section, the focus of attention will shift towards screening and ranking of objectives and technologies to reach the intended solution of MPS problem. With so many materials and manufacturing processes, MPS becomes a tiresome task. Earlier in the days, 'past experience' was used as a method to select materials and manufacturing processes. But today, this experience must be combined with new optimization techniques in order to stay on a path of constant improvement (Farag, 2014). An overview of the existing MOO and MCDM methods is shown in Figure 2.13. The paragraphs to follow will provide a brief review of each of them.

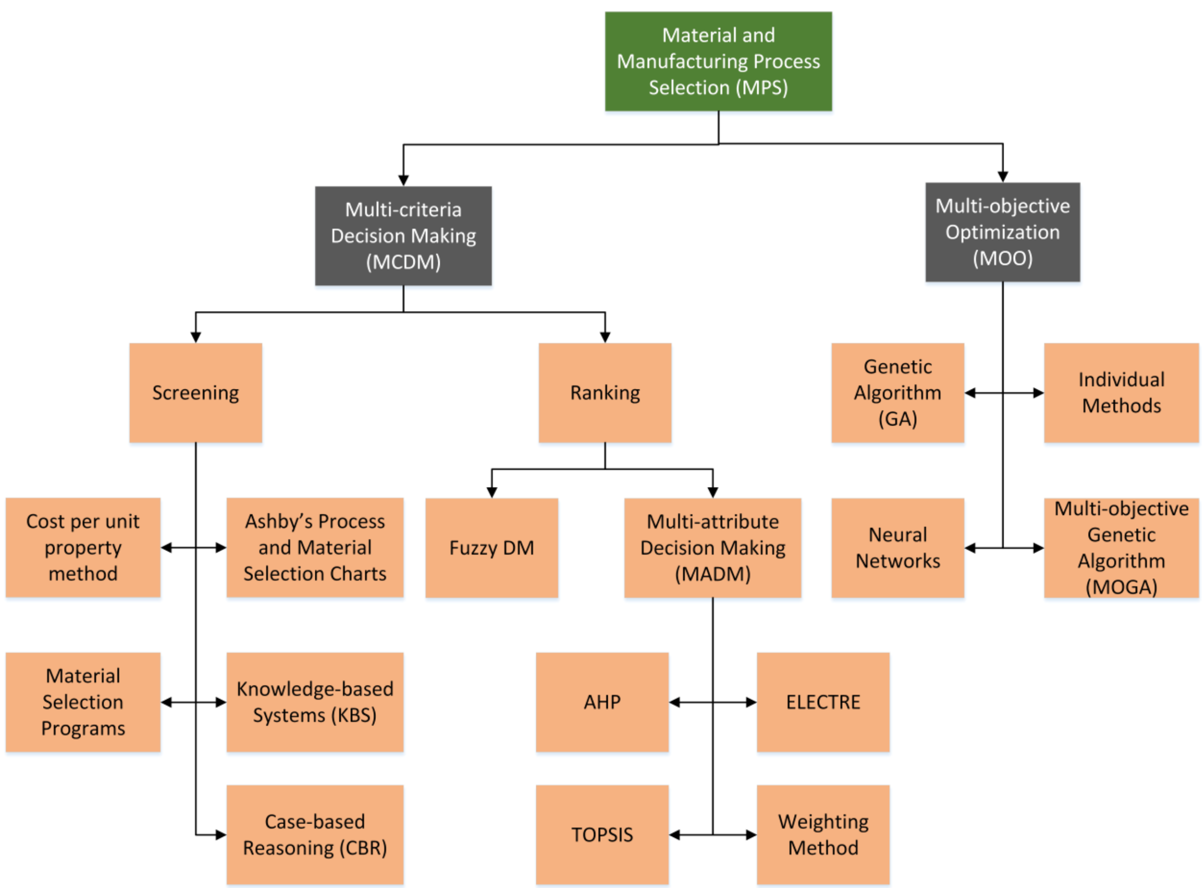


Figure 2.13. Methods for Material and Manufacturing Process Selection

2.3.1 Multi-objective Optimization (MOO)

MOO refers to finding the best solution from a set of given solutions. By employing MOO, the basic idea of finding a single solution changes to finding a set of ‘good compromises’, which are also referred to as ‘Pareto optimals’ or non-dominated solutions (Caramia and Dell’Olmo, 2008). Ashby (1999) used MOO in material design and selection by minimizing a performance metric. The objective function contained one or more performance metrics and each metric depended on certain control variables such as dimensions of the component, thermal and mechanical loads it may carry, and the material properties. He also identified various trade-off surfaces on which the best choices lied.

Multi-objective material selection was also used by Zhou et al. (2009) for drink containers by using Genetic Algorithm (GA) and neural network. They focused on material selection for sustainable products and evaluated indicators like mechanical, economic and environment properties for selection. The mechanical properties included attributes such as strength, density, stiffness, etc.; economic properties included purchase cost, process cost, etc.; while, environment properties constituted attributes like environmental pollution, energy consumption, etc. The Artificial Neural Network (ANN) and GA were used in parallel and materials such as glass, aluminum, steel and zinc for fizzy drinks, and PVC, PP and High-Density Polyethylene (HDPE), were evaluated for packaging liquids like milk and juices. Smith et. al (2002) also proved that neural networks provide good input settings to attain the necessary mechanical and physical properties of a material especially when designs are linked with process requirements. Moreover, to find the relationship between performance requirements and properties of a plastic IM part, Shi (2005) used back propagation neural network. He then selected the required material by employing a fuzzy model. Neural networks were also used by Li et al. (2004) and Amoiralis et al. (2006) to find materials for gears and power transformers, respectively (Jahan et al., 2010).

Considering the performance indices and availability constraints, Ramadan (2016) used non-linear binary programming and GA for MPS by minimizing the total manufacturing cost. The cost was divided in to two parts: direct material cost which depends on the quantity of selected material, and conversion cost (includes direct labor and overhead costs) which is a function of selected manufacturing process. Sakundarini et al. (2013) also used GA for choosing the best material in the preliminary design stage by considering factors such as function and recyclability. They considered thickness, length, height of parts and material type as the design variables while the geometric size was considered a constraint. ABS was chosen as the suitable material among ABS, Polyethylene Terephthalate (PET), Poly-propylene (PP), Polystyrene (PS) and Polyvinyl Chloride (PVC) which were ranked based on factors such as stiffness, minimum cost and recyclability.

Considering 'Individual Methods', Farag and El-Magd (1992) used a benefit-cost analysis to consider the optimum design-material-process combination for a sailing boat mast. They considered the design limitations such as plastic yielding, local buckling, global buckling and internal fibre buckling for fibre-reinforced materials. The major performance requirements were chosen as yield strength, modulus of elasticity, specific gravity and cost. Furthermore, Finite Element (FE) simulations were used by Najafi and Rais-Rohani (2012) for concurrent process-product design optimization. They modeled manufacturing effects such as elastic stress-strain relationships, yield surface, and flow rule hardening. The effects were then coupled with manufacturing processes such as deep drawing, spring-back, joining and trimming, and the effect of manufacturing processes on product performance was studied.

But all the methods discussed above involve minimizing one or few objective functions. As the number of objective functions and the associated constraints increase, more effort is invested by the algorithms to search the solution space, i.e., more computing time is required for convergence. Moreover, as the output is a set of viable options and not a single solution, the MPS problem is more diversely addressed in the literature by the MCDM methods in which decision makers identify the most preferred solution either by ranking or screening or both (modeFRONTIER, 2008).

2.3.2 Multi-Criteria Decision Making (MCDM)

MCDM refers to a problem that involves multiple and conflicting goals. The idea is to get one solution which is a good compromise and acceptable to the entire team. Moreover, 'screening' and 'ranking' are two different domains. Screening refers to plucking out the irrelevant options based on generated requirements. The process of ranking, in continuation of screening, then ranks different alternatives on basis of constraints and objectives. Furthermore, Jahan et al. (2010) split the ‘ranking’ methods in to two groups; Multi-Attribute Decision Making (MADM) methods, and fuzzy MCDM methods. MADM problem refers to the selection of an optimal technology resource from two or more viable manufacturing processes/group of manufacturing processes based on two or more attributes (Rao and Davim, 2008). As, MPS involves various attributes’ and requirements’ evaluation, therefore, it can rely on MADM techniques. Fuzzy MCDM, instead, was developed by Zadeh in 1965 to address imprecise, unclear and ambiguous problems. It is a multi-valued logic in which the assessment of attributes is not on the basis of conventional yes/no and true/false, but in linguistic terms like good, fair, best, poor, etc. (Khabbaz et al., 2009). Giachetti (1997) believed that as MPS problem is dealt with during early stages of the design, it is affected by imprecise requirements, conditions and parameters, a problem suited for Fuzzy Logic (FL). Related to selection criteria in AM, Lan et al. (2005) provided a hierarchical structure. The decision criteria were classified into five categories; technology (the parameters dealing with capability of the specific technology), geometry (the geometrical flexibility offered by the AM system), performance (the parameters relating to the mechanical properties of the fabricated parts), economy (including the total operational costs of using a specific AM system), and productivity (including those parameters dealing with manufacturing time). The structure is shown in Figure 2.14.

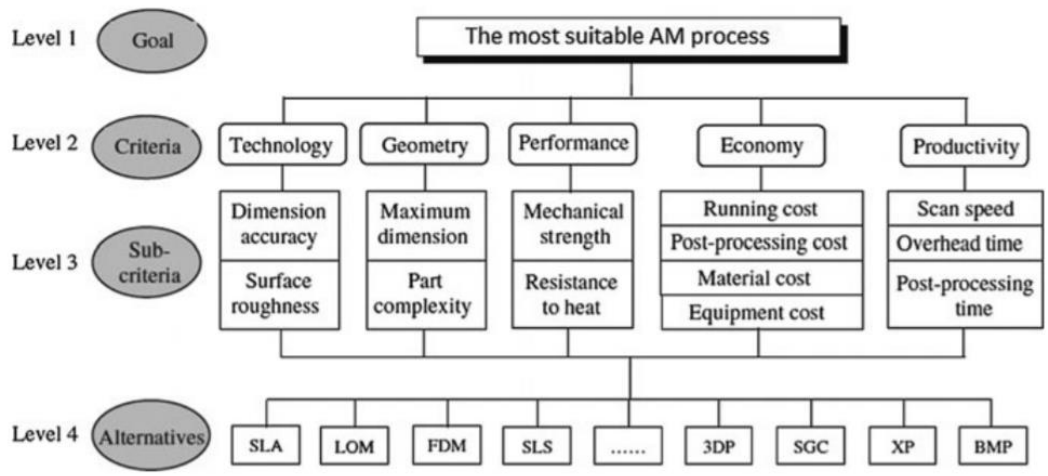


Figure 2.14. Hierarchical AM technology selection and criteria (Lan et al., 2005)

Based on the information in Figure 2.13, the subsequent paragraphs provide state of the art related to screening and ranking methods adopted in MCDM MPS. The techniques have been discussed both in relation to MPS in AM and otherwise.

2.3.2.1 Screening Methods

For screening purposes, 'Cost per unit property method' is used in situations where one property stands out as the most important requirement for part functionality, but the method lacks taking into consideration all other properties (Farag, 2014). Maleque and Dyuti (2010) used this method to select optimum material for the application of folding bicycle frame. Ashby's 'materials and process selection charts' have also been used with great success by the Cambridge Engineering Selector (CES) for initial screening of materials and processes. Ashby (2005) proposed a generic material selection strategy; design requirements' translation, screening of materials with the help of constraints, ranking of materials using the function objectives, and using support information with the help of material and process selection charts. The drawback, however, is that the method focuses on one or few objectives such as minimizing weight (Jahan et al. 2010).

Case-Based Reasoning (CBR) was also used by few authors but the disadvantage lies with its working principle which focuses on the best practices of the past pertaining to a case which may or may not be fully authentic. CBR was used by Berman et al. (2015) for material selection in petro-chemistry by using ARAMIS and AIR/CAIR selection methods. ARAMIS has the capability of handling both numerical and verbal estimates while AIR/CAIR uses voting procedures to reach required course of action. CBR was also employed by Bernard et al. (2003) to construct a Computer Aided Process Planning (CAPP) expert system to aid in choosing RM processes.

'Material Selection Programs' were used by some authors to find suitable materials (Chen et al., 1995; Kumar and Singh, 2007). These programs/tools assist the consumer to clearly specify the requirements and in turn the product designer in early stages of material selection. For instance, Kesteren et al. (2007) used three tools for the selection of materials viz. a viz. picture tool (showing pictures of product examples with their materials), sample tool (showing actual material samples) and question tool (showing the sensorial aspects of materials during several phases of user interaction). Such programs/tools are good for screening but can't perform calculations and are usually used as databases. MPS problems usually employ such databases but they have their shortcomings. Firstly, there are very few MPS systems which have the manufacturing process searching capability and application of these systems on complex product developments can be a daunting task. For example, for a sophisticated design, the tool may conduct multiple screening stages to reach final solution which will require lot of time. Secondly, the data covered in these tools may not be sufficient. Many MPS systems just focus specific types and grades of materials.

Lastly, Knowledge-based systems (KBS) were used for screening purposes which rely on artificial intelligence and search in a database of information. Hornberger developed the first RP process selector in 1993 (Khorram and Nonino, 2018) followed by the development of a database of RP system capabilities to assist RP users in making the most efficient use of the selected RP system (Campbell and Bernie, 1996). Furthermore, Masood and Soo (2002) introduced a rule based expert system to select an RP system from all the commercially available RP systems manufacturers in USA, Japan, Germany and Israel. An RP process selector was also developed by Chung et al. (2003) based on entity relationship techniques. Related to decision making in two stages, an expert system and a fuzzy approach was developed by Lan et al. (2005) to generate and rank feasible alternatives, respectively. In addition, Djassemi (2009) used multi-criteria deductive KBS for MPS of an oil pump by taking in to consideration the technical performances and environmental constraints. Ipek et al. (2013) also improved the sustainability of products for the case of automotive sector by proposing a KBS to select appropriate materials. Zha (2005) further used fuzzy KBS in concurrent design in terms of total production cost. The author developed a prototype Web-based knowledge intensive Manufacturing Consulting Service System (WebMCSS) to help designers in choosing the suitable materials and manufacturing processes at the conceptual level of design.

Consequently, considering the methods discussed above, it is evident that screening methods alone are not sufficient. They need to be used in combination with ranking methods for effective solution of MPS problems.

2.3.2.2. Ranking Methods

‘Analytical Hierarchy Process (AHP)’ is the most widely and successfully used MADM method in MPS ranking. It can have as many levels as required to fully address a particular problem and can effectively handle both objective and subjective attributes by obtaining relative weights of the criteria (Rao, 2013). Gupta et al. (2015) worked on AHP in sustainable manufacturing to evaluate priority of product metrics. They analyzed sustainable manufacturing practices such as eco-design, process design, lean practices, green supply chain, product recovery and cleaner production for making electrical panels. Desai et al. (2012) also used AHP in conjunction with DFM to provide more flexibility to include multiple criteria for decision making for MPS problem. Moreover, Armillotta (2007) used an adaptive AHP decision model to select suitable AM process from a set of alternatives for prototypes made from a selected category (conceptual model, technical prototype, sand casting, investment casting and plastic molding). The attributes included fast build, good accuracy, low material cost, etc. Further, in AM MPS, AHP is applied to material selection in gears (Yazdani and Jahan, 2017), selection of non-traditional machining processes, defining weight coefficients for selection of manufacturing processes in conceptual design stage for the body of modular hip joint endoprosthesis (Lukic et al., 2017), and selection of best material for design of lightweight aircraft metallic structures (Adhikari and Mirshamsm 2017). The only drawback AHP carries is concerning the independence of all the attributes (Singh et al., 2015). In addition, Zaman et al., 2018a presented a novel generic decision methodology based on MCDM methods; material selection charts and AHP, to suggest the best compromise of materials, manufacturing processes and machines for AM technology.

Furthermore, 'Technique of Ranking Preferences by Similarity to Ideal Solution (TOPSIS)', was developed to choose the best alternative given a finite number of criteria. Milani et al. (2006) used TOPSIS to study the effect of normalization norms on ranking of materials with respect to material selection for gears. Byun and Lee (2005) identified six attributes for the selection and evaluation of AM processes via TOPSIS; accuracy, surface finish, elongation, cost of part (includes material and labor cost), tensile strength and build time (includes pre-processing time, build time and post-processing time). Chakladar and Chakraborty (2008) also proposed a combined TOPSIS-AHP approach to select the most appropriate non-traditional machining process (ultrasonic machining, abrasive jet machining, laser beam melting, etc.) for a specific work material and shape feature (holes, through cavities, surfacing and through cutting) combination. They also answered questions such as when and why a process is not suitable for a given machining application and why a process should not be selected despite being acceptable.

ELECTRE, another of the MADM methods, has been used by various authors for MPS problem with majority focusing on material selection only. Shanian and Savadogo (2006) used ELECTRE IV for bipolar of polymer material selection while ELECTRE III was used by Shanian et al. (2008) for selecting material in a group considering weighting uncertainty.

Last of all, Jahan et al. (2012) devised a framework considering the 'weighting method' in ranking of material selection. Their work considered the dependency between criteria, such as Brinell hardness number and ultimate tensile strength, and claimed to have improved the MADM ranking methods by providing a systematic approach for subjective, objective and correlated weights. Here, subjective weights are based on an expert evaluation and best practices, objective weights are derived from the data that is known about the problem, and correlated weights are a combination of subjective and objective weights.

2.3.3 Conclusion

The current section provided an overview of the selection strategies used in MPS with special focus on MCDM techniques and the associated screening and ranking methods for AM. The optimal selection of various AM processes therefore, carries a hierarchical nature and is categorized by geometry, technology, performance, economy and productivity.

2.4 Gap Analysis

A thorough yet critical attempt was made to review the available literature to identify the shortcomings in the field of IPPD with respect to nearly all areas of application. All the literature discussed focused on the integrated approach with more emphasis on modification of DFM for AM and using a combination of the design criteria (e.g., function, cost and environment) and the DFM/DfAM guidelines for successful generation and utilization of the design requirements and attributes. In case of MPS problem which is also an integral decision-making aspect of DFM itself, a lot of work was done on traditional domain with researches involving cost per unit property methods, material and process selection charts, CBR, material selection programs, KBS, AHP, TOPSIS, and ELECTRE III, but very little in the AM area. However, the use of AHP for MPS in AM was found out to be quite promising in the literature reviewed. This also opens a window of opportunity to apply AHP for MPS in AM since it is the most widely and successfully used MCDM method. It is also evident from literature that AHP has been applied extensively on problems either small-scale or large-scale and having multiple criteria. It is suitable for multiple domains, especially in manufacturing sector as it relies on the innate human inclination to conduct comparison by catering both subjective and objective attributes (Emrouznejad and Marra, 2017).

Since, (70-80) % of the cost is incurred due to the manufacturability of the part, it is necessary to provide flexibility to change process parameters early in the design phase. Moreover, as there are numerous materials available today with various manufacturing processes, there is a need to develop a generic decision methodology that can consider all areas of application (e.g. aerospace, automotive, health care, etc.) for design criteria such as function, cost and environment. The methodology should also take in to account the available DfAM guidelines to generate the requirements and attributes to manufacture a part.

Furthermore, for a product in focus, there are always two perspectives involved; one related to the designer and the other related to the manufacturer. With the designer's perspective, design criteria such as function, cost and environment have more weight than the process data. More focus is given to optimization of the topology, shape, size and micro level enhancements of the part as discussed in the literature reviewed. This has grabbed a lot of attention from MOO domain as their methods suite the designer's perspective more. But as we move to the manufacturer's perspective, the element of 'pick and choose', i.e., MCDM methods come into consideration. With a large solution space available with various materials and manufacturing processes, a manufacturer works in two distinct domains; one, where materials and their respective properties have a strong influence on product design and processing capabilities, and two, where finite set of materials and manufacturing processes restrict the luxury of design modifications too often.

Moreover, it is evident that MPS is a three-step process. First step involves evaluation of design criteria considering the functional requirements, available cost data and environmental impact. The second step screens the relevant material classes and manufacturing processes, and the third step ranks the alternatives available to help in final MPS. Few methods such as the MOGA, Chart method, 'weighting method', AHP and FL stand out when it comes to MPS problem, with each having its own advantages and disadvantages. In addition, the design activity can be divided in to 3 main stages; conceptual, embodiment and detail designs. Only few studies have worked on the MPS in conceptual (Albinana and Vila, 2012) and embodiment design stages (Gupta et al., 2003) as detail design is largely shadowed by product-oriented modifications such as topology optimization, etc.

Therefore, based on the expansive literature reviewed and over-arching aim of this research, it has been found that the methods proposed in the literature either focused on the designer's perspective wherein DfAM was catered to address the relationship between product and process data by using the same high level methodology while each phase of DfAM was not clear, or they focused on the manufacturer's perspective which concentrated on the theory of 'pick and choose' with the AHP leading by being the most reliable method. Moreover, the studies were either function-specific or application-specific. It is hence, necessary to simultaneously consider the manufacturing constraints and considerations, customer requirements, the existing pool of available AM materials and the corresponding AM manufacturing processes to optimize design criteria for MPS. Following are the areas which were focused in respect to MPS for AM in the subject thesis:

1. Considering the saturation level attained by AM technology, it was necessary to devise a method which can consider all areas of application (aerospace, motor vehicles, health care, consumer products/electronics and academic institutions, industrial applications,

architecture, and government/military) and propose generic approximate weights for the each of the considered design criteria (e.g., function, cost, environment, etc.).

2. The criteria to identify the suitability of any part to be manufactured by an AM process needs to be selected early in the design phase to avoid downstream time lags and incurred cost. The issues pertaining to AM technology effect each selection criteria and need to be catered for in parallel. The questions such as what kinds of features a product has, what type of material is the user interested in to build the part, and what should be the number of units produced, should be answered well in advance.
3. DFM, DfAM and DFX are vast topics with lots of research done. The motive behind reviewing the literature was to get a fair amount of idea related to the available guidelines and rules, and how they work for each of AM and TM technologies. Therefore, the available DFX guidelines for AM technology were intended to be embedded in the proposed methodology to reach the required solution of MPS problem.
4. Collection of material properties for various metals and non-metals with reference to different AM processes is an integral part of the design of any component. There is hence, a need to structure a database which can house such properties.
5. With respect to each of the design criteria discussed, attributes need to be identified and provided room for the application of MCDM methods.
6. For each of the design stages; conceptual, embodiment and detailed, the coupling between materials, component size and processes, cost interaction among processes, and sustainability indicators of materials, needs to be considered.
7. More attention is required on MPS via sustainable design as very little research is available on the material and manufacturing process selection for such a case via MCDM methods.
8. AM process parameters significantly affect the manufacturability of the end-product. There is therefore, a need to study the process parameters in detail via practical experiments in relation to various design criteria.

Section 3

Theoretical and Experimental Research

Chapter 3: Proposed Decision Methodology

Product and process design are dynamic entities that involve accomplishing the goals that are derived from evaluating the technologies at hand and the status of the issue. Since, attaining a competitive margin and maximizing the profit margin is the objective for most of the companies today, the MPS problem has become an inter-disciplinary effort that requires inputs from all quarters of design and production teams. But as discussed in the literature review in Section 2, it is imperative to have the liberty to change the design of a product under study well within the design phase to decrease the costs of manufacturability later in the production cycle. Also, the incompatibility between materials and manufacturing processes can affect decisions regarding important parameters such as geometry.

Therefore, based on the identified gap in Section 2.4, the decision methodology proposed in this chapter follows a step by step procedure to attain AM material-process-machine combinations for a product under study / floated need. The procedure contains three major steps; translation, screening and ranking, and is being dominated globally by DfAM guidelines and the application type. The methodology also interacts with 2 independent databases; one for the AM materials and the second for AM process-machine combinations. Moreover, since the design activity can be divided in to 3 main stages; conceptual, embodiment and detail designs, the coupling between materials, component size and processes, cost interaction among processes, and sustainability indicators of materials, need to be considered for each stage. Strategies such as rule-based system approach (Zarandi et al., 2011) have been widely used to help in knowledge acquisition, choosing the selection criteria, building hierarchical definition of knowledge, selection of a user interface, and finally the implementation. But prior to all this, it is necessary to capture the voice of the customer in terms of needs, specifications, aesthetic preferences, and constraints, to formulate requirements and functionality (Deng and Edwards, 2007).

Figure 3.1 shows the global view (summary) of the proposed IPPD decision-oriented framework for MPS in AM for each of the conceptual and embodiment design stages.

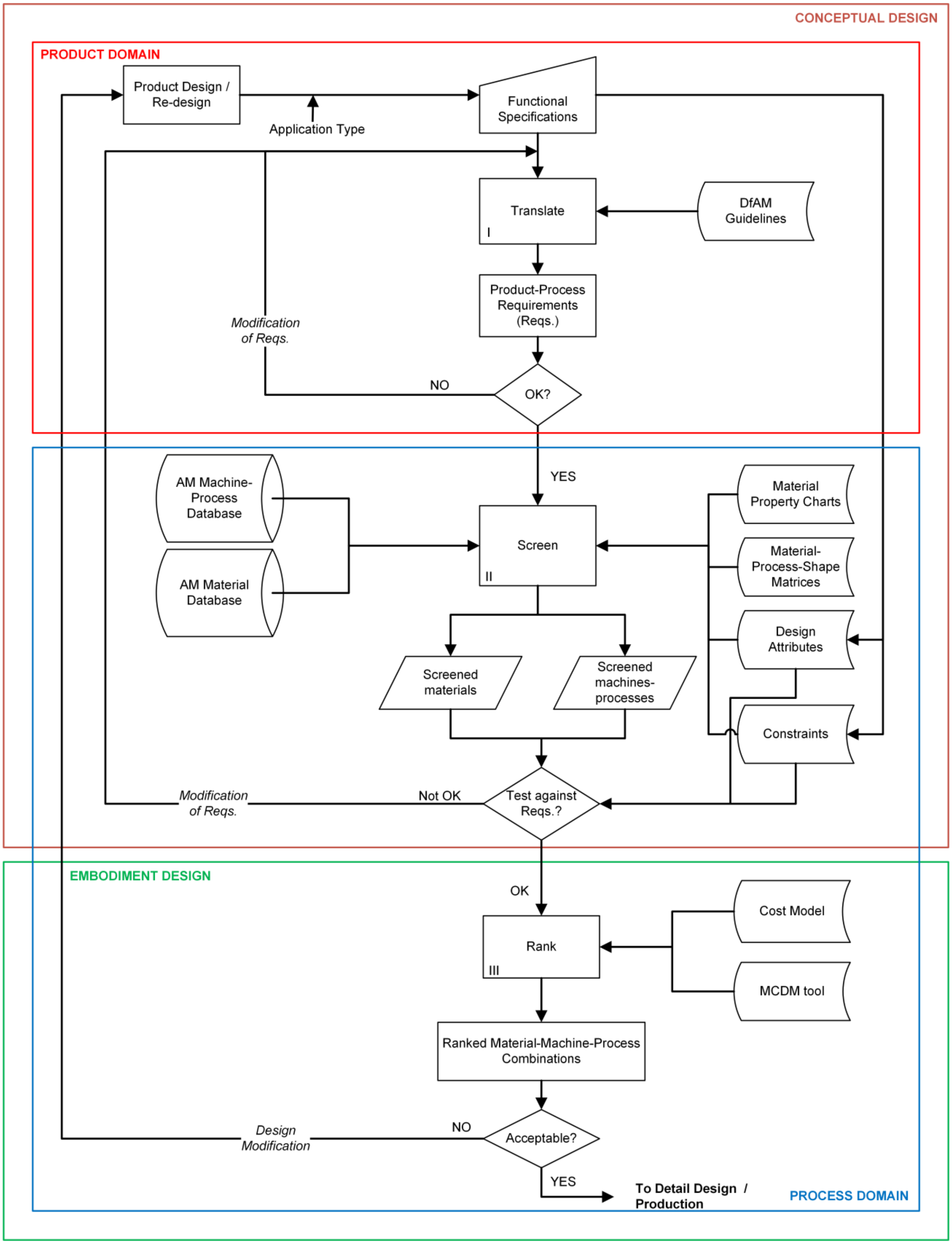


Figure 3.1. IPPD-oriented decision framework for MPS in AM

Furthermore, to structure the decision hierarchy, the framework explores the potentials of AM and suggests respective measures with the help of reviewed literature as shown in Figure 3.2. The inner circle represents the potentials of AM such as complexity for free, individualization, etc., while the outer circle shows the measures that need to be taken to achieve each of the shown potentials. It is however imperative to note that both the measures and the potentials listed are not exhaustive and are intended to guide the designer / user to follow the correct design direction from the start.

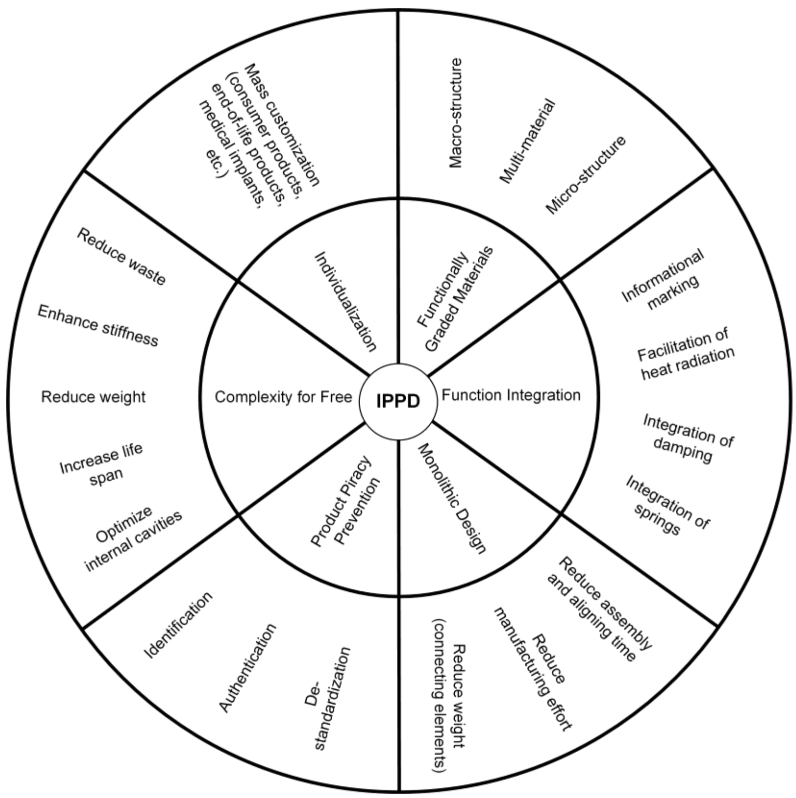


Figure 3.2. Potentials and respective measures of AM (developed by author)

The overall framework in Figure 3.1 is dissected in the text to follow to target every domain in detail with respect to MPS in conjunction with the associated design stages, i.e., conceptual and embodiment design.

3.1 Conceptual Design

Conceptual design, in context of IPPD, is considered the key stage of design process where the designer explores the fundamental scientific principles, DfAM guidelines, constraints, and associated relations, to structure an embodiment that can realize later in a design which satisfies the floated need. In conceptual design, the level of detail is not high enough, but the decisions that are adopted will condition future development and have a major impact on product quality, cost and market success (Paul and Beitz, 1996). Moreover, the effective structuring of the need statement to extract respective product and process requirements or utilizing the existing design to get the associated requirements from the functional specifications, is the most important head start for the conceptual design phase.

In addition, conceptual design involves decision making on various fronts. The proposed methodology has considered three design criteria; function, cost and environment, and each of the criterion are associated with unique decisions that act as 'selection fronts' for the decision making in MPS. They are termed as technical decisions, economic decisions and sustainability decisions, respectively (Zaman et al., 2018b). Technical decisions are related to the performance of the product; economic decisions govern the viability and cost preferences; while, sustainability decisions are associated to environmental impact of AM materials in terms of landfill waste and recyclability. The AM materials and processes impact all 3 decisions. However, AM machines only impact technical and economic decisions since the subject thesis is analysing environmental aspects related to materials and processes only. Moreover, the generated product-process requirements directly impact the decisions and AM materials, while the constraints structure the selection procedures to determine the resources.

This further implies that amidst multiple criteria, attributes, deliverables and their interactions in a conflicting manner, decision making for MPS becomes a tedious task. An attempt has been made to show the glimpse of a possible decision dilemma in Figure 3.3 (based on Figure 3.2). For instance, for the attribute 'number of parts' to be built by an AM process, if the design is 'simple', more parts can be made but if the design is 'complex', fewer parts will be built considering 'time to market' as a constraint. Similarly, number of parts directly influence AM processes which govern the selection of AM machines and materials.

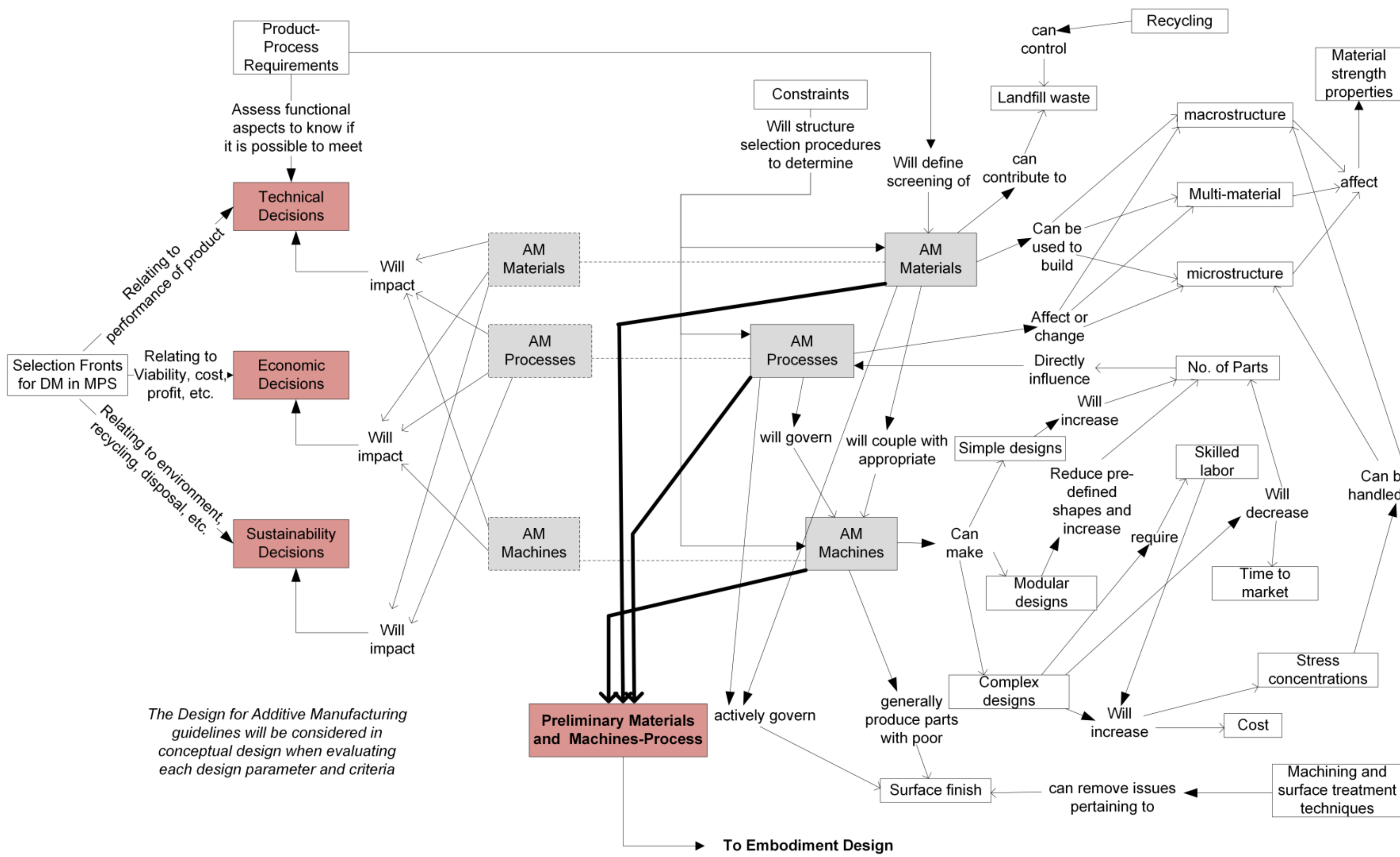


Figure 3.3. Conceptual design decision dilemma: An Example

3.1.1 Translation of Requirements

The effective identification of requirements and functionalities requires a system that can not only collect the information but also evaluate its importance. Each product requirement is a documented need regarding a characteristic or capability appreciated by users. In the current step (see Figure 3.4), the designer uses the extracted functional specifications from the CAD model (includes objective, geometry assessment, definition of constraints, identification of free variables and other relevant data) and generates a set of requirements that can be either design-related, production-related, process-related, or a combination of any of the three, based on the application type and the available DfAM guidelines. Specifically, for the application type, an "applications' filter" was created with the help of reviewed literature as shown in Table 3.1. The filter gives generic information on the applications pertaining to a chosen area and the subsequent selection criteria suitable along with the materials used commonly. The loading capacity in the subject table refers to generic association towards high speed applications (highly loaded) and low speed applications (lightly loaded). The methodology has the flexibility to modify design if the requirements generated are not as per the functional specifications. It is however important to note here that the process is in early stages of design.

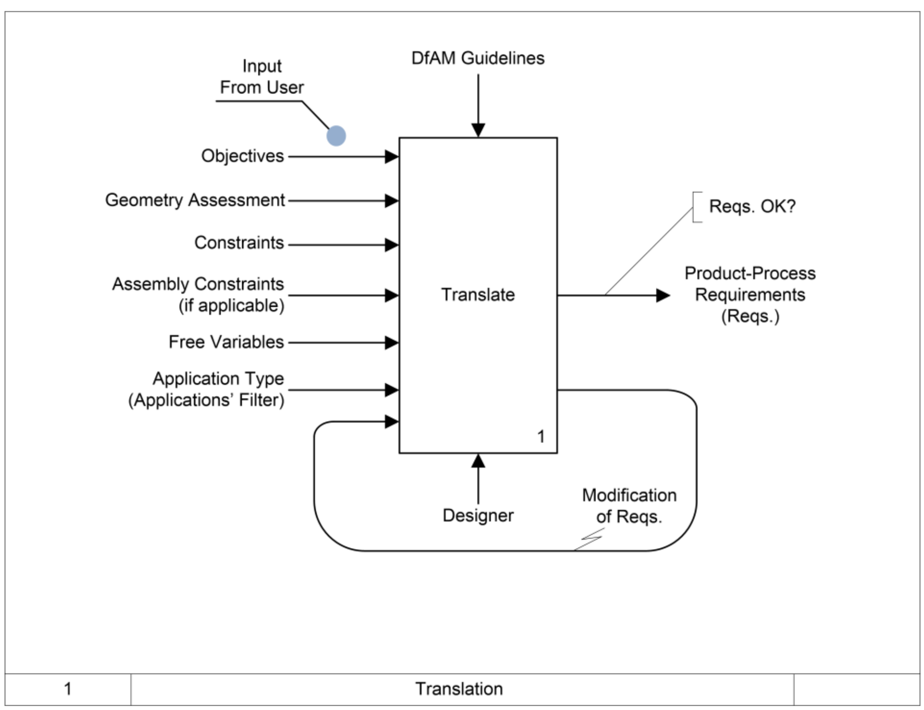


Figure 3.4. Translation of product-process requirements

Global Filter					
Sr. No.	**AM Application**	**Selection Criteria**	**Loading capacity**	**Current Applications**	**Materials used commonly**
1	Aerospace (Aero)	Operations Efficiency Weight and Material Cost Savings	Lightly loaded Highly loaded	Concept Modelling and Prototyping Structural and non-structural production parts Low volume replacement parts Thrust reverser doors Landing gears Gimbal eye Fuel Injection nozzles	Titanium alloys Cobalt Chromium alloys Stainless Steels Nickel based alloys Polyetherimide resins
2	Motor vehicles (Auto)	Operations Efficiency Weight and Material Cost Savings	Lightly loaded Highly loaded	Small quantities of structural and functional components like engine exhausts, drive shafts, gear box components, and braking system for luxury, low volume vehicles Functional components for racing vehicles Smaller volume, custom run speedometer housings, shrouds and fairings for motor cycles	Titanium alloys Cobalt Chromium alloys Stainless Steels ABS
3	Health Care (HC)	Functions Integration	Lightly loaded	Fabrication of custom made prostheses and implants, medical devices, biological chips, tissue scaffolds, living constructs, drug screening models, and surgical planning & training apparatus	Titanium alloys Cobalt Chromium alloys Stainless Steels ABS, Polyamides nylon, photopolymers
4	Consumer Products/Electronics, Academic Institutions, and Other (CP)	Customization	Non-structurally loaded Lightly loaded	Toys, figurines, furniture, office accessories, musical instruments, art, jewellery, museum displays, and fashion products	ABS, PC, SS, nylon, glass filled polyamide, epoxy resins, wax and photopolymers Cobalt Chromium alloys
5	Industrial Applications (IA)	Operations Efficiency Weight and Material Cost Savings	Lightly loaded Highly loaded	Creation of end products that apply mechanical force to perform work	Titanium alloys Cobalt Chromium alloys Stainless Steels Nickel based alloys ABS
6	Architecture (Arch)	Functions Integration	Lightly loaded	Modelling of structures and designs	ABS, thermo-plastic polymers
7	Government/Military (G/M)	Operations Efficiency Weight and Material Cost Savings	Lightly loaded Highly loaded	For metal parts, heat exchangers, and use in remotely piloted vehicles.	Titanium alloys Cobalt Chromium alloys Stainless Steels Nickel based alloys Polyetherimide resins

Table 3.1. Global Applications' Filter

3.1.2 Screening of AM Materials and Manufacturing Processes

Once the requirements are approved, Ashby's charts (Ashby, 2010) are used for screening. Each of the charts summarize material properties and process attributes by mapping the areas of property space occupied by each material class (see Section 2.2.1, Figure 2.8). The charts assist in picking a subset of materials with a property within a specified range. For instance, one needs to pick materials with modulus (E) between 100 and 200 GPa or with a thermal conductivity above 100 W/mK. Similarly, performance is maximized by selecting the subset of materials with the greatest value of a grouping of material properties. For example, a light, stiff beam is best made of a material with a high value of $E^{1/2}/\ \rho$; safe pressure vessels are best constructed from a material with a high value of $K_{Ic}^{1/2}/\sigma_f$, and so on. Multiple criteria can also be used. Figure 3.5 shows one of the many charts available for screening.

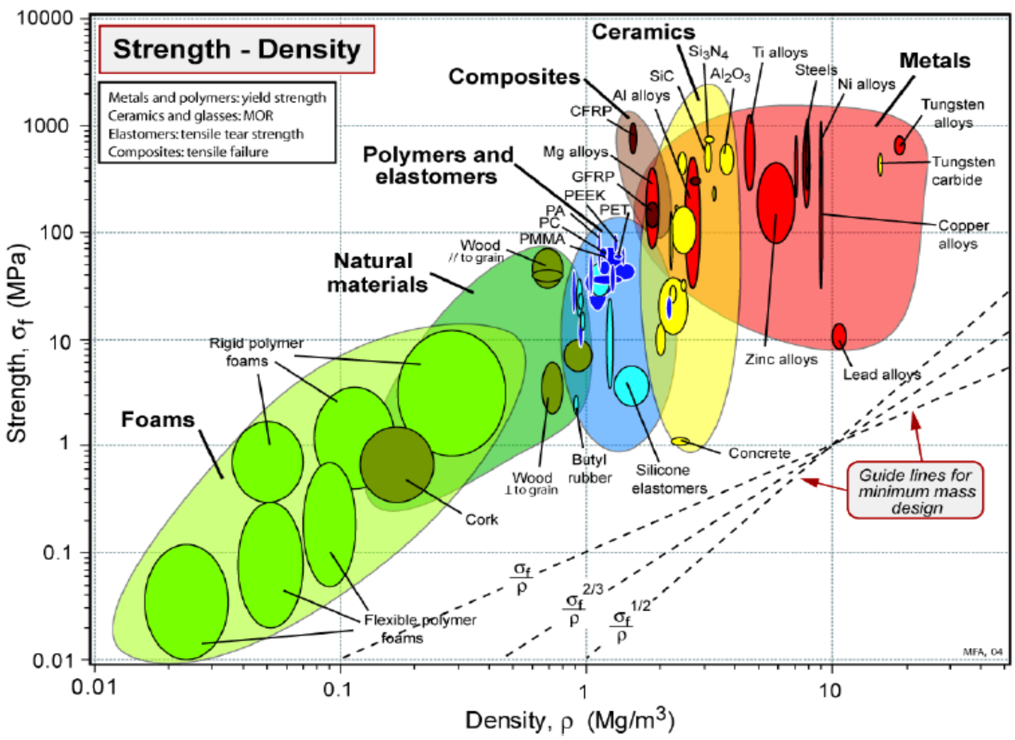


Figure 3.5. Chart for Strength against density (An Example)

Moreover, a manufacturing task has attributes, such as density, cost, strength, etc., and the objective is to maximize or minimize either or some of them to achieve the functional requirements of the part. These are also referred to as the 'performance indices' like strength-to-weight ratio (σ_f/ρ), stiffness-to-weight ratio (E/ρ), etc. The material indices suggested by Ashby (2005) and used in the current thesis for screening of AM concerned materials and manufacturing processes, are shown in Table 3.2.

Material Indices	
Function, objective and constraints	**Index**
Tie, minimum weight, stiffness prescribed	$\frac{E}{\rho}$
Beam, minimum weight, stiffness prescribed	$\frac{E^{1/2}}{\rho}$
Beam, minimum weight, strength prescribed	$\frac{\sigma_y^{2/3}}{\rho}$
Beam, minimum cost, stiffness prescribed	$\frac{E^{1/2}}{C_m\rho}$
Beam, minimum cost, strength prescribed	$\frac{\sigma_y^{2/3}}{C_m\rho}$
Column, minimum cost, buckling load prescribed	$\frac{E^{1/2}}{C_m\rho}$
Spring, minimum weight for given energy storage	$\frac{\sigma_y^2}{E_\rho}$
Thermal insulation, minimum cost, heat flux prescribed	$\frac{1}{\lambda C_p\rho}$
Electromagnet, maximum field, temperature rise prescribed	$\frac{C_p\rho}{\rho_e}$

ρ = Density, E = Young's modulus, σ_y = elastic limit, C_m = cost/kg, λ = thermal conductivity, ρ_e = electrical resistivity, C_p = specific heat

Table 3.2. Material Indices suggested by Ashby (2005)

3.1.2.1 Databases for AM materials and manufacturing processes

As collection of material properties for various metals and non-metals with reference to different AM processes is an integral part of the design of any component (suggested in Section 2.4), there was a need to structure a database which can house such properties. Therefore, two databases were constructed; each for the materials and machines related to the AM technology.

<u>Database for materials</u>

For the AM materials, the database constituted commercially available materials used in various AM machines. The database can be expanded as new materials and production technologies of AM are added with the passage of time. The characteristics for the materials used in the repository are included in Table 3.3. The database might not be exhaustive, but it can provide a comprehensive outlook on majority of the materials used in AM machines today.

A part of the material database for both metals and non-metals is shown in Annexure A.

Characteristics	Unit	Description
Material	-	Type of material used in AM machine
Process	-	Type of AM process (refer to Table 2.1 for details)
Machine	-	Type of AM machine as per AM process
Yield Strength	MPa	Stress endured before plastic deformation
Tensile Strength	MPa	Resistance of material to break under load
Ductility at Break	%	Amount a material stretches before breakage
Density	kg/mm^3	Density of material
K_s	-	Support structure factor
Kr	-	Recycling factor
Surface Finish	μm	Value of roughness on material
Material Usage Efficiency	%	Amount of material that can be used after recycling
Material Cost per kg	US$/kg	Cost of material per kilogram
Support Material Cost	US$	Cost of support material used to build support structure (if required)
Environmental Impact	-	Environmental impact of material after disposal
Landfill Waste	-	Landfill waste contributed by material

Table 3.3. Characteristics for material database

The characteristics are self-explanatory. However, for the environmental impact and landfill waste, both were assumed 'equal' for all material comparisons under study. Similarly, the material usage efficiency was also assumed to be 100%. All these assumptions were undertaken to ease the computation process.

Database for machines

The machine database provided data for 134 AM machines available commercially today. The whole lot was divided into three groups; personal, professional and production. The classification was inspired both from literature as well as the division already being used by the three leading AM technology vendors, i.e., 3D Systems, Stratasys and EOS GmbH. As far as the classification from vendors is concerned, it targets the area of application where the machine is being used, as well as the size of the part being built. The scan speed, build chamber size, minimum layer thickness, machine cost, etc., are the factors that both the vendors and the subject thesis used to categorize the machines in the database.

On the literature front, Mancanares et al. (2015) used the same classification to select AM processes based on parts selection criteria. The authors used a limited 45 different machines from the top 3 vendors of AM technology. Furthermore, a near classification can also be witnessed in a research report published by Bechthold et al. (2015). 'Personal' machines included the ones that can be used for personal/desktop use as well as on the lower step of industrial printers for business. 'Professional' machines generally comprised of purposes such as prototyping before full-scale production and required a certain skill set. Such machines require an open space such as an office with a good ventilation. Lastly, the 'Production' machines utilized high level of automation and control of processes to not only print prototypes but also final consumer products. These machines required a shop floor environment along with a dedicated operator. Table 3.4 shows the AM processes and manufacturers listed in the database.

Category	AM Process	AM Manufacturer
Personal	SLA	3D Systems, DWS Lab
	3DP	Voxeljet, ExOne
	DLP	DWS Lab, Rapidshape, MoonRay, Autodesk, B9CreatoR, UNCIA 3D, Kudo 3D, Colido DLP
	FDM	3D Systems, Stratasys, Makerbot, RepRap, Raise3D, TierTime
	MJM	Stratasys
	LENS	Optomec
	LOM	Mcor Technologies, Solido
	SLM	Concept Laser, Realizer
Professional	3DP	Voxeljet, ExOne
	SLA	XYZ Printing, Formlabs, DWS Lab
	CJP	3D Systems
	DLP	Rapidshape, Morpheus
	FDM	Stratasys, Makerbot, Raise3D, TierTime, Essential Dynamics
	MJM	3D Systems, Solidscape, Stratasys
	SAS	Asiga
	LENS	Optomec
	LOM	Mcor Technologies, Solido
	SLM	EOS, SLM Solutions, Concept Laser, Realizer, Renishaw, 3Geometry
	SLS	EOS, Blueprinter
Production	3DP	Voxeljet, ExOne
	SLA	3D Systems, Lithoz
	DLP	EnvisionTEC, Rapidshape
	FDM	Stratasys, DeltaWasp, TierTime
	MJM	Stratasys
	DMP	3D Systems
	SLM	SLM Solutions, Concept Laser, Renishaw, EOS, 3Geometry
	SLS	3D Systems, EOS
	EBM	Arcam
	EBAM	Sciaky
	LENS	Optomec
	LMD	BeAM

Table 3.4. AM process and vendors used in the machine database

A similar part of the machine database is shown in Annexure B for reference. Moreover, the characteristics of AM machines used in the database are listed in Table 3.5.

Characteristics	Unit	Description
Category	-	Type of category the machine belongs to (personal, professional, production)
Manufacturer	-	Name of manufacturer
Machine	-	Name of AM machine
AM Process	-	Type of AM process
Build materials	-	Type of materials used to build a part
Support materials	-	Type of materials used for support structure (if required)
Applications	-	Areas of application for the AM machine
Layer thickness	µm	Minimum layer thickness achieved during part build
Accuracy	mm	Minimum deviation in part dimension from original on successive builds
Build volume	mm^3	Total volume of space available for part build in a machine
Printing Speed	mm/h	Average speed to build a part with dimensions (50 x 50 x 20) mm^3
Volume build rate	l/h or kg/h	Amount of material deposited by a machine per hour
Machine Cost	US$	Cost of AM machine
Post-processing	Yes/No	Indicator to identify if post-processing is required for a manufactured part
Application	0 / 1	Application area(s) where the machine can be used (0 = machine not used, 1 = machine is used)

Table 3.5. Characteristics for machine database

The complete data flow for the screening phase are shown in Figure 3.6 and Figure 3.7 showing screening of AM materials and AM machines, respectively:

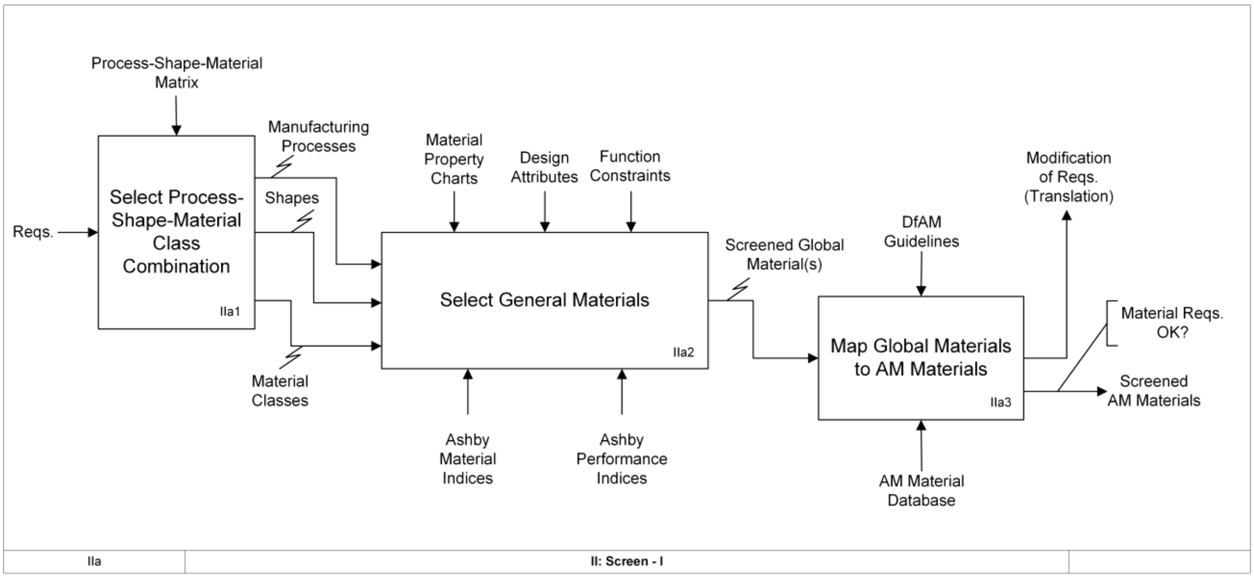


Figure 3.6. Screening of AM Materials

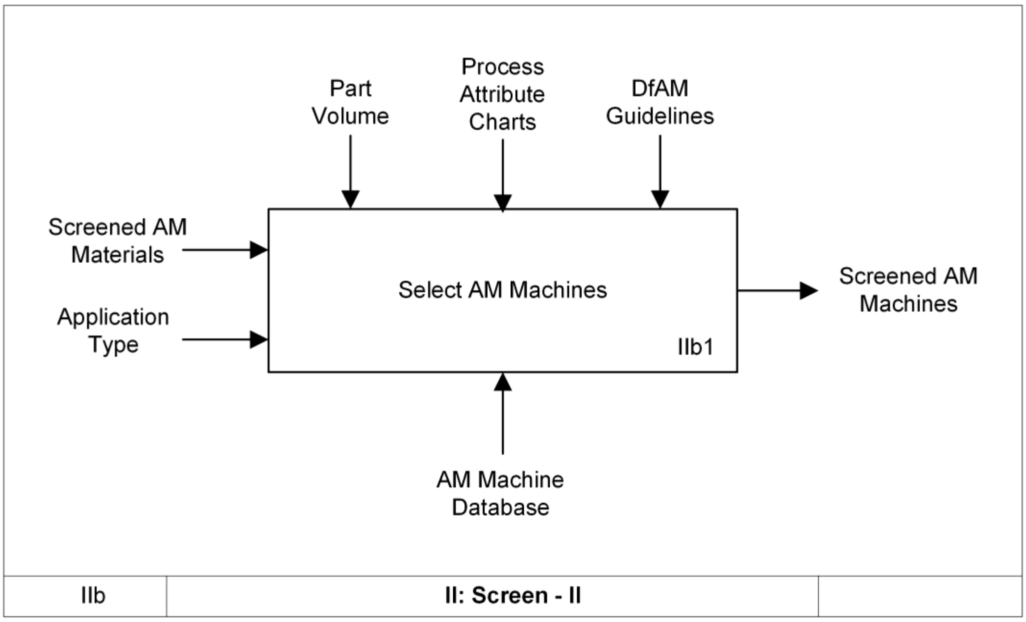


Figure 3.7. Screening of AM Machines

For the first screening process (Figure 3.6), the translated requirements (Reqs.) from Figure 3.4 are passed to the first process hub, i.e., 'select process-shape-material class combination'. The stage is further assisted by the devised process-shape-material matrix (see Annexure C). For the matrix, it is assumed that the AM process can make any shape following the notion of 'complexity for free'. However, each process is limited by the type of material class used. The result of hub 'IIa1' is the first set of screened materials, shapes and manufacturing processes. This set of data is then fed to the second hub, i.e., 'select general materials' which utilizes support from material property charts (Figure 3.5), design attributes and function constraints. Both the attributes and constraints are derived from the functional specifications generated from the CAD model. The whole process of hub 'IIa2' is controlled by Ashby's material and performance indices (Table 3.2). The output is a set of screened global materials. The term 'global' refers to the fact that the materials obtained follow the conventional naming such as ABS, PC, etc. However, for the AM naming of materials, many behave like ABS and PC, but their names are very different such as Accura 60, VisiJet CR-WT, etc. Therefore, it is important at this stage to map the global materials to AM materials using the materials database and DfAM guidelines (process hub IIa3). The output for the first screening process is hence, a set of AM materials that can be mapped within the machine database. There is also a quality check at this stage to see if the materials adhere to the requirements generated with a flexibility to re-define requirements by sending to the translation hub.

The second screening process is related with the screening of AM machines (Figure 3.7). The screened set of AM materials from Figure 3.6 are fed to the process hub 'select AM Machines'. As the machine database heavily relies on the application type, the area of application will provide the initial set of machines. Based on the characteristics of the machine database (Table 3.5), the part volume, process attributes and DfAM guidelines guide in providing the final set of screened AM machines.

Both the screened AM materials and machines are then tested against the requirements which are dominated by constraints and design attributes (derived from functional specifications). If they adhere to the test, the set of materials and machines are forwarded to the embodiment design stage for ranking. It is also imperative to note here that the conceptual design stage involves both the product and the process domain (Figure 3.1) thereby reinforcing the idea of IPPD used in this thesis.

3.2 Embodiment Design

The embodiment design stage is referred to as the 'detailed inspiration' wherein a design is developed in accordance with engineering and economic criteria. Both the materials and processes can be classified hierarchically at this stage. Usually, process planning stage governs the decisions that deal with the selection of processes while decisions for the selection of materials are made during the detailed design stage (Gupta et al., 2003). However, in this thesis both the material and process selection are attempted in the embodiment design stage to ensure first-hand information for the designers to later reduce the cost due to manufacturability. The embodiment design stage is governed by the ranking procedure of alternatives related to both the screened AM materials and machines (Zaman et al., 2018a). The procedure is explained in the paragraphs to follow. It is however imperative to note that in the development of products that require collaboration among different organisations/teams, life cycle and knowledge must be managed in such a way that a 'compromised' yet ''win–win'' relations are produced that have repercussions on the competitive advantage of all the collaborators. Consequently, management of the life cycle of the product implies structured 'decision-making' in design (Albinana and Vila, 2012).

3.2.1 Ranking of AM Materials and Manufacturing Processes

The process of ranking allowed for the application of MCDM tools and any associated cost models for selection of the compromised set of resources for AM, based on design attributes and functional constraints. The procedure was validated by (1) Classical AHP, which was utilized because all the attributes were assumed to be independent (see section 2.3.2.2 for more details), and (2) cost model adopted by Yim and Rosen (2012). Each of the two sub-processes are explained in the text to follow.

3.2.1.1 AHP

The classical AHP has the overall objective or goal at the top level, criteria and sub-criteria at the middle level and various alternatives at the lowest level. The data in each level is tabulated in a square matrix *(n)* whose diagonal elements are 1 and the *(j, i)* element of the matrix is the reciprocal of the *(i, j)* element. Here *i* is the row index and *j* is the column index. A scale is used to do the pair-wise comparison of the same hierarchy elements in each level which is listed in Table 3.6. The scaling process yields a relative priority or weight of elements with respect to criterion or element of the highest level. For all the elements in a level, the comparisons are performed with respect to all the elements in the level above.

Scale	**Numeric Assessment**	**Reciprocal**
Extremely preferred	9	1/9
Very, very strong	8	1/8
Very strong	7	1/7
Strong plus	6	1/6
Strongly preferred	5	1/5
Moderate plus	4	1/4
Moderately preferred	3	1/3
Weak plus	2	1/2
Equally preferred	1	1

Table 3.6. Relative scale of criterion (Saaty, 2008)

When all the contributions of the elements in a level with respect to all elements in a higher level are added, the final / global weights of the elements at the lowest level are found. Once the pair-wise comparison of alternatives or sub-criteria is made with respect to an element in a higher criterion (formed as matrix), the largest eigenvalue (λ_{max}) should be approximately equal to the number of elements in the comparison matrix (n). The deviation of λ_{max} from n is a measure of the consistency of judgement of the decision maker (Dweiri and Al-Oqla, 2006). The consistency index is found using the following formula:

$$CI = \lambda_{max} - n/n - 1$$

The consistency ratio (CR) is found by:

$$CR = CI/RI$$

where RI is a random index of the same order matrix as shown in Table 3.7.

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.58

Table 3.7. RI for factors used in the decision-making process (Dweiri and Al-Oqla, 2006)

Generically, if CR ≤ 0.1, the consistency is acceptable.

The working procedure of AHP for MPS of AM technology is given in Figure 3.8. Each of the design criteria – function, cost and environment – were split into machine and material-related parameters to decompose the problem for viable pair-wise individual comparisons at material and machine level. The material parameters/attributes included material strength properties, surface finish, material cost, material usage efficiency, environmental impact, and landfill waste. In addition, the machine parameters/attributes included geometry complexity, accuracy, minimum layer thickness, build volume, machine cost, labor cost, and build speed. The parameters provided a healthy blend of product and process attributes for a good compromise of MPS for AM technology. Moreover, subjective and objective weights are included for all areas of application. The subjective weights were utilized when the application areas and the design criteria were considered collectively, and objective weights were assigned to each of the sub-criteria to rate their level of importance in the overall analysis.

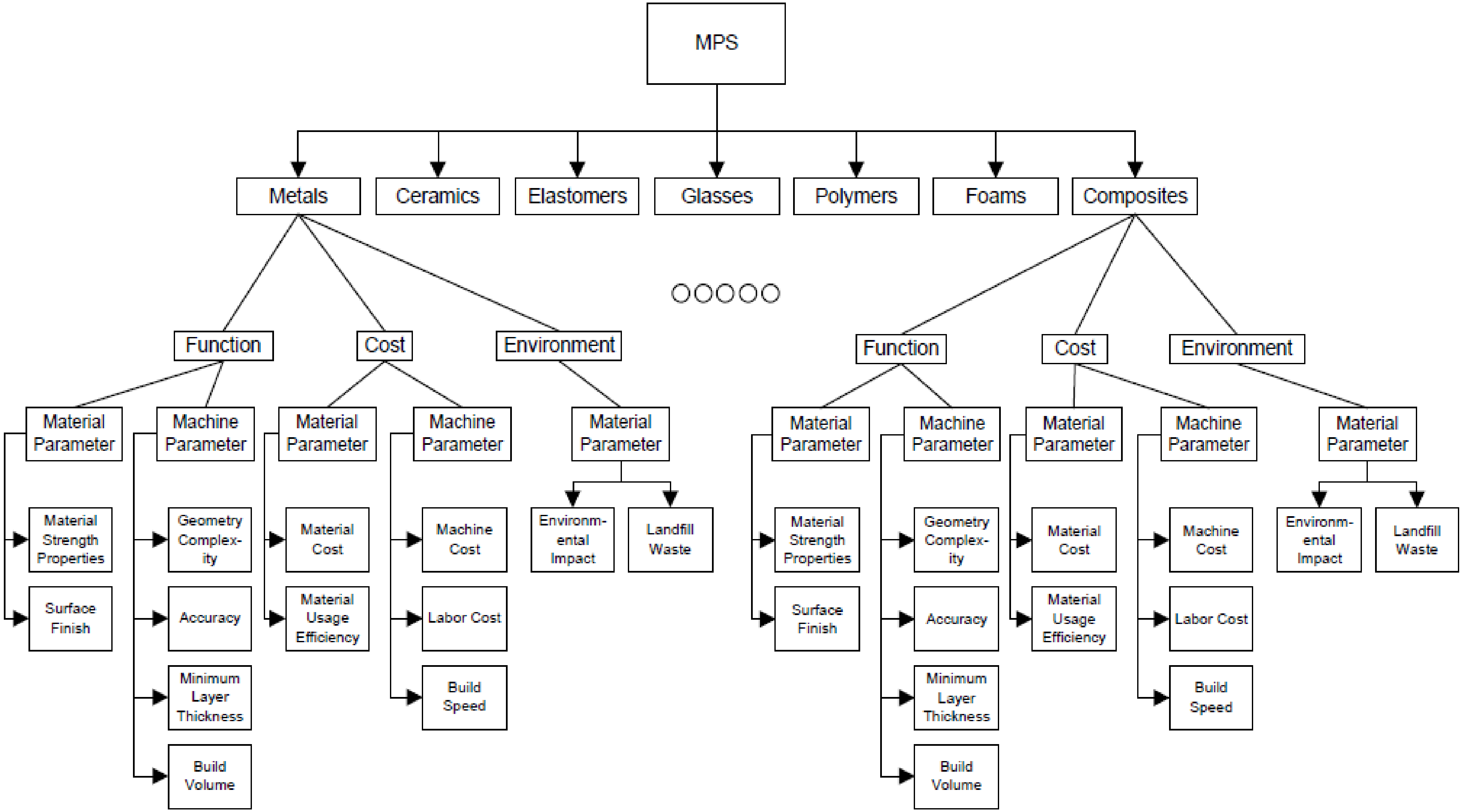


Figure 3.8. AHP Decision Structure

3.2.1.2 Cost Model for Overall Material Cost

The cost model adopted by Yim and Rosen (2012) was chosen for finding the overall material cost for an AM material. As per the literature reviewed, the selected cost model was applicable on a wide range of AM processes in early stages of design. The particular cost model was used to assess how it can facilitate the decision making for AM MPS. The cost model is given by the following equation.

$$M = K_s \times K_r \times N \times v \times C_m \times \rho$$

where, M = overall material cost (US$), K_s = support structure factor, K_r = recycling factor, N = number of parts, v = part volume (mm^3), C_m = material rate per unit weight (US$/kg) and ρ = material density (kg/mm^3). K_s is used to capture cost of additional material usage for building support structures and is usually in the range of 1.1 – 1.5 while K_r is used to find the cost contribution of wasting loose powder which is not recycled after the build. K_r usually lies in the range of 1 – 7.

The result of 'ranking' is a compromised yet acceptable set of AM materials and manufacturing machines for a derived AM manufacturing process. The complete information and data flow for the ranking of AM materials and machines-processes is given in Figure 3.9.

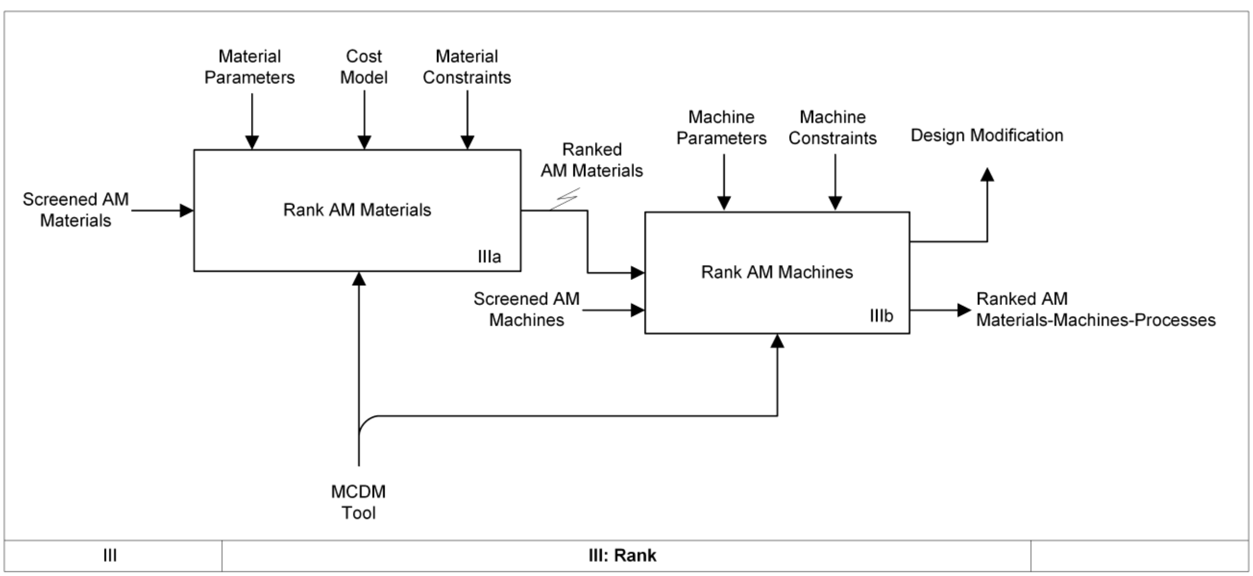


Figure 3.9. Ranking of AM materials and machines-processes.

The screened AM materials from the output of Figure 3.6 are fed to process hub IIIa (rank AM materials). Material parameters, constraints and the cost model are used as controlling parameters to help rank the AM materials using an MCDM tool such as AHP. The ranked materials are then input to the process hub IIIb (rank AM machines) where using machine parameters and constraints, the machines are ranked and clubbed with the materials and processes. At this stage, if the ranked material-machine-process combinations are acceptable, they are forwarded to detail design section / production. If not, the methodology is routed to the start of Figure 3.1 where the design is modified to regenerate functional specifications and the subsequent product and process requirements.

3.3 Conclusion

Consequently, the methodology proposed in this chapter used translation, screening and ranking procedures to select the best compromise of AM materials, manufacturing processes and machines by considering both the subjective and objective weights. It employed step by step and easy to implement procedures in conjunction with the DfAM guidelines, application type, functional constraints, and part requirements to generate material and machine combinations for a given AM manufacturing process(es). The subsequent chapter (Chapter 4) will apply the methodology on an industrial case study from the aerospace industry.

Chapter 4: Application on Industrial Case Study

To validate the methodology, an industrial case study was used which was based on a 'drilling grid' used in an aerospace industry to drill holes with precision and accuracy on the sides of the aircraft body. As a conventional industrial practice, drilling grids are manufactured with aluminium alloys using traditional material removal processes, such as conventional machining. Furthermore, twenty-four hours' time margin is available for the design, validation and delivery of the grids in the aerospace industry, but this deadline is usually not followed. Missing drilling grids can occur due to late definition / modification of design; impossible repairing after defective status is flagged and fatigue impact on quality. Also, grids can reach up to 50 kg when handled by one operator in worst ergonomic conditions such as under the aircraft fuselage. Moreover, since the part is not big (50 x 50 x 20) mm, manufacturing within the aircraft body will save time, cost and logistics. Therefore, the objective of the current section was to assess the best compromise of AM materials and processes for building the drilling grid that can fulfil the functional requirements and time constraints. The drilling grid is shown in Figure 4.1.

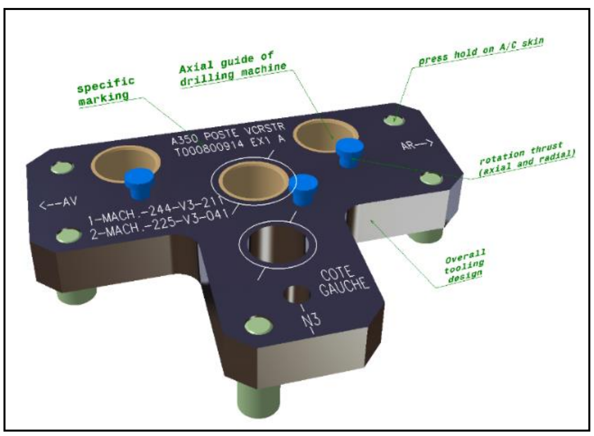


Figure 4.1. Drilling Grid

4.1 MPS Data Collection

The purpose of this phase was to conduct a brainstorming session with the concerned experts in the aerospace industry. A generic question and answer session was designed with the purpose of gathering data for the translation of functional specifications. Questions were e-mailed to the selected experts before the actual interviews. Face-to-face interviews were then conducted.

This technique of data collection was chosen so that the preference and views of the interviewees could be accounted for. The experts preferred non-metallic material for the manufacture of the part. Moreover, the experts participated voluntarily in this research. The functional specifications generated are listed in Table 4.1.

Factor	Description
Objective	Maximize Strength
Constraints	▪The length of the holes should be 20 millimeter (mm)
	▪For locking screws, the part shall withstand
	✓ an axial load of 120 daN (1200 N)
	✓ a radial load of 250 daN (2500 N)
	▪For holes H1, H2 and H3, the part must withstand radial force of 37 daN (370 N)
	▪For holes H2, H3 and H4, the part shall withstand an axial force of 500 daN (5000 N)
	▪Deformation should not exceed 0.0931 mm
	▪Internal forces should not exceed 1.29 × 108 N/m^2
	▪Dimensional tolerance should be maintained at 1/10th of mm.
Geometry	Pad = 3D solid
Assessment	Locking Screws = Circular Prismatic
	Clamps = Circular Prismatic
	Pad Supports = Circular Prismatic
Free Variables	AM Machine / Process
	AM Material

Table 4.1. Functional specifications for drilling grid

4.2 Screening of AM materials and machines

Ashby's charts and material indices related to maximizing strength and stiffness were used to screen the first global set of materials based on the generated functional specifications. Since, the drilling grid can be interpreted as a 'beam', three material indices were used as guidelines of minimum mass and cost on Ashby's charts (see Table 3.2), i.e., $\frac{E^{1/2}}{\rho}$, $\frac{\sigma_f{}^{2/3}}{\rho}$ $\frac{\sigma_y{}^{2/3}}{\rho}$ and $\frac{\sigma_y{}^{2/3}}{C_m\rho}$, where ρ = density, E = Young's modulus, σ_y = Elastic limit, σ_f = strength, and C_m = cost/kg. The charts used for first set of screening are shown in Figures 4.2 and 4.3.

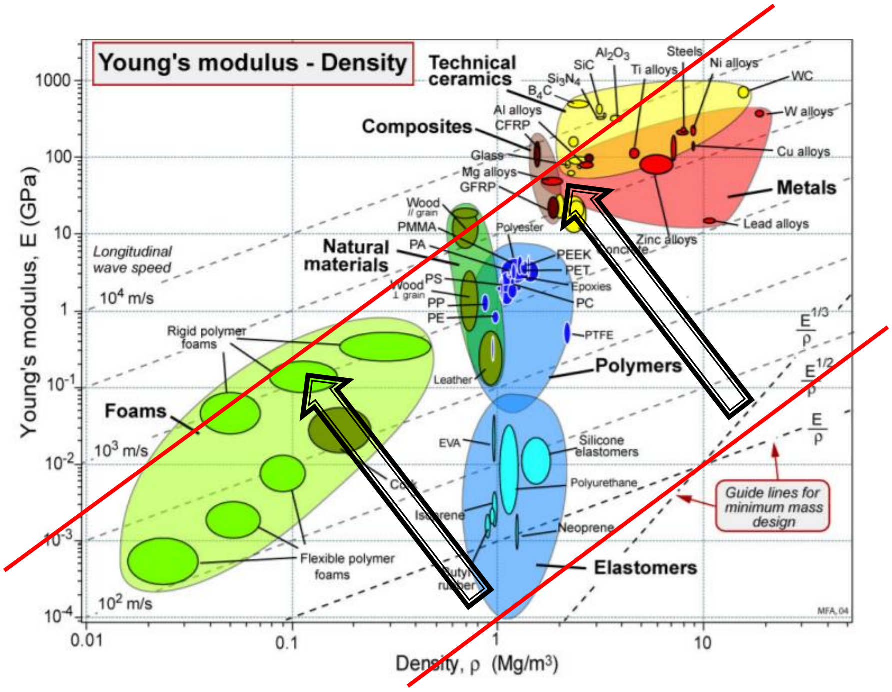


Figure 4.2. Young's modulus, E, against Density, ρ

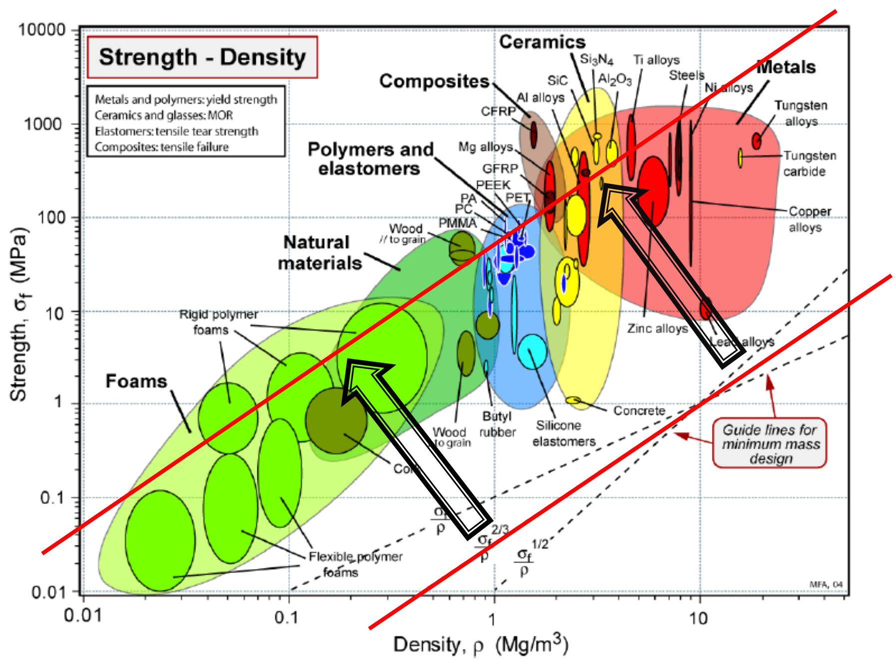


Figure 4.3. Strength, σ_f, against Density, ρ

The guidelines for minimum cost design are translated up in the direction of arrows as per the functional specifications. The methodology follows the property 'strength' because the surface of the aircraft body is not flat but rather in curvature. Therefore, to drill the holes, relationship based on Young's modulus vs density (Figure 4.2), strength vs density (Figure 4.3), Young's modulus vs relative cost per unit volume (see Annexure D), and strength vs relative cost per unit volume (see Annexure D) are used. Since the preference was for non-metallic materials, the global set of materials included Acrylonitrile Butadiene Styrene (ABS)-, Polypropylene (PP)-, and Polycarbonate (PC)-related materials. Each of the global materials were then used to find the associated materials in the materials' database for different AM processes. Similarly, considering the area of application, i.e. aerospace, the relevant machines were also screened from the machines' database. Few more materials such as 'Nylon' were added to the final list as they displayed the functional specifications generated earlier for the drilling grid. The final set of screened AM materials, processes and machines are listed in Table 4.2.

Manufacturer	Machine	AM process	Materials
3D systems	ProJet MJP 2500 series	MJM	VisiJet M2 RBK
			VisiJet M2 RCL
			VisiJet M2 RWT
	ProJet 3510/3500/3600	MJM	VisiJet M3-X
	ProJet 5000	MJM	VisiJet M5 Black
			VisiJet M5 MX
			VisiJet M5-X
	ProJet MJP 5500X	MJM	VisiJet CR-CL
			VisiJet CR-WT
Asiga	PICO2 / Freeform PRO2	SAS	Plas
EnvisionTEC	P4 MINI XL	DLP	RC31
			RC90
	P4 Standard XL	DLP	R11
			RCP 30
			R5 Gray
			RC31
			ABflex
			ABStuff
Stratasys	Fortus 380 mc 450 mc / 250 mc/ 900 mc	FDM	ABS plus (250 mc)
			ABSi (900mc)
			ABS-M30 (380/450 mc, 900mc)
			ABS-M30i (380/450 mc, 900mc)
			ABS ES-D7 (380/450 mc, 900mc)

		ASA (380/450 mc) Nylon 6 (900 mc) Nylon 12 (380/450 mc, 900 mc) PC (380/450 mc, 900mc) PCABS(900mc) PC ISO (380/450 mc, 900mc) PPSF/PPSU (900mc) ULTEM 1010 (380/450 mc) ULTEM 9085(380/450 mc, 900mc)
Objet 1000 Plus	MJM	Rigur (RGD 450, 430) Vero Family (RGD 835, 850, 840, 875) DIGITAL ABS Ivory/ABS2 Ivory

Table 4.2. Screened set of AM materials, processes and machines

4.3 Ranking of AM materials and machines

To facilitate the pairwise comparisons by AHP, the materials listed in Table 4.2 were grouped as per the 'base material'. For example, all materials either showing properties of ABS or looked like ABS were separated and grouped under ABS such as ABS-M30, ABS-ESD7, ABSi, ABS-M30i, PCABS, ABS Plus, VisiJet M3-X, VisiJet M5-X, VisiJet CR-WT, DIGITAL ABS, ABStuff and Plas. The same procedure was followed for PC- and PP- related materials. The materials left after this grouping were collected in another set. The AHP was conducted as explained previously in Section 3.2.1.1 and Figure 3.8. As the concerned AM processes (as per Table 4.2) included MJM, SAS, DLP and FDM, the cost parameters for each process are listed in Table 4.3 (see Section 3.2.1.2 for more details on the model used). Since, all our screened AM processes were not using powder-based ones, the values of K_r remained 1.0 for all of them. The value of K_r increases as more powder-based materials are used.

Parameters	**MJM**	**SAS**	**DLP**	**FDM**
C_m (US$/kg)*	340.9	450	339.2	339
K_s	1.1	1.1	1.3	1.3
K_r	1.0	1.0	1.0	1.0
N	1	1	1	1
v (mm^3)	46,000	46,000	46,000	46,000

* average material rate per unit weight

Table 4.3. Cost model parameters for drilling grid

For the case of ABS-related materials and material attribute ‘material strength properties’, Table 4.4 shows one of the several decision matrices used for comparison. The rest of the matrices for all other material attributes generated for ABS-related materials are listed in Annexure E.

	ABS-M30	**ABS-ESD7**	**ABSi**	**ABS-M30i**	**PCABS**	**ABS Plus**	**VisiJet M3-X**	**VisiJet M5-X**	**VisiJet CR-WT**	**DIGITAL ABS**	**ABStuff**	**Plas**
ABS-M30	1	2	3	3	1/3	1	1/5	1/4	1/5	1/6	1/3	1/2
ABS-ESD7	1/2	1	2	1	1/3	2	1/3	1/3	1/4	1/6	1/3	1/3
ABSi	1/3	1/2	1	1	1/2	1/2	1/5	1/2	1/3	1/6	1/4	1/4
ABS-M30i	1/3	1	1	1	1	1/2	1/3	1/2	1/5	1/6	1/3	1/3
PCABS	3	3	2	1	1	3	1/3	2	1/2	1/6	1/4	1/2
ABS Plus	1	1/2	2	2	1/3	1	1/2	1/2	1/3	1/5	1	1/2
VisiJet M3-X	5	3	5	3	3	2	1	4	4	2	2	3
VisiJet M5-X	4	3	2	2	1/2	2	1/4	1	3	1/5	2	2
VisiJet CR-WT	5	4	3	5	2	3	1/4	1/3	1	1/5	1/3	1
DIGITAL ABS	6	6	6	6	6	5	1/2	5	5	1	3	4
ABStuff	3	3	4	3	4	1	1/2	1/2	3	1/3	1	1
Plas	2	3	4	3	2	2	1/3	1/2	1	1/4	1	1

Table 4.4. Decision matrix of the AHP for material attribute ‘material strength properties’ (ABS-related)

The results from all material comparisons from each set are therefore listed in Table 4.5.

Rank	**ABS-related**	**PP-related**	**PC-related**	**Nylon-related**	**Remaining**
#1	DIGITAL ABS	RGD 450	PC	Nylon 6	RGD 875
#2	VisiJet M3-X	RGD 430	PC ISO	Nylon 12	ULTEM 1010
#3		VisiJet M5 Black	VisiJet M2 RCL	-	ULTEM 9085
#4	VisiJet M5-X	VisiJet M5-X	VisiJet CR-CL	-	R5 Gray
#5	VisiJet CR-WT	-	-	-	R 11
#6	Plas	-	-	-	PPSF
#7	ABS Plus	-	-	-	RCP 30
#8	ABS-M30	-	-	-	VisiJet M2 RWT
#9	ABS-ESD7	-	-	-	RC 90
#10	ABS-M30i	-	-	-	VisiJet M5 MX
#11	ABSi	-	-	-	VisiJet M2 RBK
#12	-	-	-	-	ASA

Table 4.5. Results of the AHP for material comparisons

As per the results displayed in Table 4.5, DIGITAL ABS, RGD 450, PC, PC ISO, Nylon 6, RGD 875 and ULTEM 1010 were selected. These materials were matched with the screened machines in Table 4.2 to generate Fortus 250 mc, Fortus 380 mc/450 mc, Fortus 900 mc and Objet 1000 Plus machines for the AHP's pair-wise comparisons. The result for machine comparison is given in Table 4.6.

Parameter	**Global Priorities (%)**	**Fortus 250 mc**	**Fortus 380 mc/450 mc**	**Fortus 900 mc**	**Objet 1000 Plus**
Geometry Complexity	11.7	0.029	0.029	0.029	0.029
Minimum Layer Thickness	14.7	0.013	0.023	0.013	0.100
Accuracy	20.2	0.023	0.063	0.102	0.014
Build Volume	12.1	0.009	0.013	0.061	0.039
Build Speed	26.9	0.026	0.113	0.113	0.017
Machine Cost	7.9	0.038	0.023	0.009	0.009
Labor Cost	6.5	0.016	0.016	0.016	0.016
	100	15.4%	28.0%	**34.3%**	22.4%

Table 4.6. Decision hierarchy for final selection of AM machine (Drilling Grid)

Each parameter in Table 4.6 is assigned a 'global priority' weightage. Through these assigned priorities, the pair-wise comparisons are executed for a final number. For example, in the same Table 4.6, if we consider the criterion 'Minimum Layer Thickness', all the four machines; Fortus 250mc, Fortus 380mc/450mc, Fortus 900mc and Objet 1000 Plus, have pair-wise comparisons with each other to generate a consolidated decision matrix using relative scale of criterion as shown in Table 3.6. The resulting matrix is shown below for better understanding:

	Fortus 250mc	Fortus 380mc/450mc	Fortus 900mc	Objet 1000 Plus
Fortus 250mc	1.0	0.5	1.0	0.14
Fortus 380mc/450mc	2.0	1.0	2.0	0.20
Fortus 900mc	1.0	0.5	1.0	0.14
Objet 1000 Plus	7.0	5.0	7.0	1.0

Table 4.7. Example: Pair-wise comparison of the selected machines for parameter 'minimum layer thickness'

Similarly, a consolidated decision matrix is generated for each criterion both in the material-parameter tree and the machine-parameter tree for each of the design criteria; function, cost and environment. Moreover, this trend of having pair-wise comparisons takes place for all the materials involved (metals, ceramics, elastomers. etc.). In our case, polymers were considered (see Table 4.5).

Consequently, the final MPS for the drilling grid included AM machine 'Fortus 900 mc' running on AM Process 'FDM' and can use any of Nylon 6, ULTEM 1010, PC and PC ISO as the AM build materials. The final set of materials proved to be a good compromise for building the drilling grid.

4.4 Comparative Analysis and Validation

To compare and validate the proposed method in Chapter 3, the same case study (drilling grid) was used and applied on another popular MCDM method for material and process selection; Simple Additive Weighting (SAW). SAW is a simple, yet effective method based on weighted average using arithmetic mean. Since, it is a proportional linear transformation of the raw data, the relative order of the magnitude of the standardized scores remains equal (Adriyendi, 2015).

Each of the criteria; function, cost and environment, were assigned weights of 77.2%, 17.3% and 5.5%, respectively, considering the emphasis of the experts on part functionality (the same as used for AHP). Each of the attributes were further assigned individual weightages with respect to materials and machines, normalized decision matrices were constructed, and the scores were calculated for each alternative. For the sake of simplicity, only the results are displayed. Moreover, the same materials as suggested in Table 4.2 were chosen for the application of SAW. Table 4.8 shows the final ranked results along with their comparison with the results generated by AHP.

Rank	Materials AHP	Score	Materials SAW	Score
#1	Digital ABS	0.203	ULTEM 1010	0.148
#2	ULTEM 1010	0.18	DIGITAL ABS	0.146
#3	RGD 875	0.167	RGD 875	0.136
#4	Nylon 6	0.153	Nylon 6	0.119
#5	RGD450	0.113	VisiJet M3-X	0.097
#6	PC	0.094	RGD 450	0.084
#7	PCISO	0.09	RGD 430	0.077
#8	-	-	PPSF/PPSU	0.066
#9	-	-	PCISO	0.065
#10	-	-	PC	0.062

Table 4.8. Ranked materials' comparison for AHP and SAW

It is evident from the results that the validation of the proposed methodology via SAW helped to generate not only the same set of materials as AHP but also assisted in exploring three more materials; VisiJet M3-X, RGD 430 and PPSF/PPSU. The generated materials were then matched with the screened machines in Table 4.2 to generate ProJet 3510/3500/3600, Fortus 250 mc, Fortus 380 mc/450 mc, Fortus 900 mc and Objet 1000 Plus machines for the SAW scoring.

The machines ranked as per the obtained scores are listed in Table 4.9.

Rank	**Machine**	**Score**
#1	Fortus 900 mc	0.25
#2	Projet 3510/3500/3600	0.23
#3	Fortus 380mc/450mc	0.20
#4	Objet 1000 Plus	0.17
#5	Fortus 250mc	0.16

Table 4.9. Ranked machines' scoring with SAW

Similarly, the final MPS for the drilling grid included AM machine 'Fortus 900 mc' running on AM Process 'FDM' and can use ULTEM 1010 as the AM build material. The material generated is in accordance with materials generated with AHP. However, some materials that were generated by AHP (Nylon 6, PC and PC ISO) came further down when generating results from SAW.

4.5 Conclusion

The current chapter provided the results of the application of the proposed methodology on a case study from the aerospace industry. It employed the MCDM techniques; AHP and SAW to validate the methodology, and the results were subsequently discussed.

Chapter 5: Process Parameter Optimization for FDM

Chapter 4 showed the application of proposed methodology on an industrial case study (drilling grid) by suggesting the appropriate MPS (material, process and machine) on system level. Nevertheless, AM is an efficient technology but over the years full scale application has been on the slower side because of the compatibility issues between materials and machines (Pilipovic et al., 2009; Zaman et al., 2018a). Two ways can be followed to overcome this situation; one, to develop new materials that are not only superior to the conventional materials but are also compatible with the specific AM technology; and two, to adjust the process parameters during fabrication stage so that the properties exhibited by the part manufactured are improved. The second approach has been quite successfully followed in recent years as the properties of the built parts rely heavily on the ‘settings’ of the process parameters used (Jain et al., 2009; Chockalingam et al., 2008). In addition, many AM design guidelines have been published to cater for the process and machine specific constraints for a material, but such guidelines only provide a starting point and do not provide information about the different kinds of AM machines and their production capabilities (Thompson et al., 2016).

As FDM was selected as the process to be used to build the drilling grid in Chapter 4, the objective of the current section was to assess the impact of FDM process parameters on the strength of the built parts by using Taguchi’s DOE. Therefore, FDM process was studied in detail. To briefly state about FDM process, it begins with the design of a digital CAD model and its conversion to STL file format. The generated STL file is fed to the built-in software of the machine which breaks it in to individual slices and assigns attributes like infill percentage and wall thickness. In addition, each sliced section represents the 2D cross section of the designed model and generates a G-code which in turn controls the FDM system (Upcraft and Fletcher, 2003). The raw material is usually PLA or ABS (filament) which is gradually taken into a heated extruder (see Figure 5.1). To ease extrusion of the raw material through the nozzle of a controlled diameter, the temperature of the material rises over its melting temperature (Srivastava and Rathee, 2018). The semi-melted material is then deposited on the layer laid previously via a print head (moves in two horizontal axes). A local sintering process of neck growth then joins both hot fibres of material. The sequence is repeated for each slice solidifying the material at the temperature of the chamber until the whole part is manufactured (Bellehumeur et al., 2004; Thirmurthulu et al., 2004). FDM has multiple applications such as the production of fit & form products, construction of conceptual models and products for future manufacturing processes, investment casting, etc.

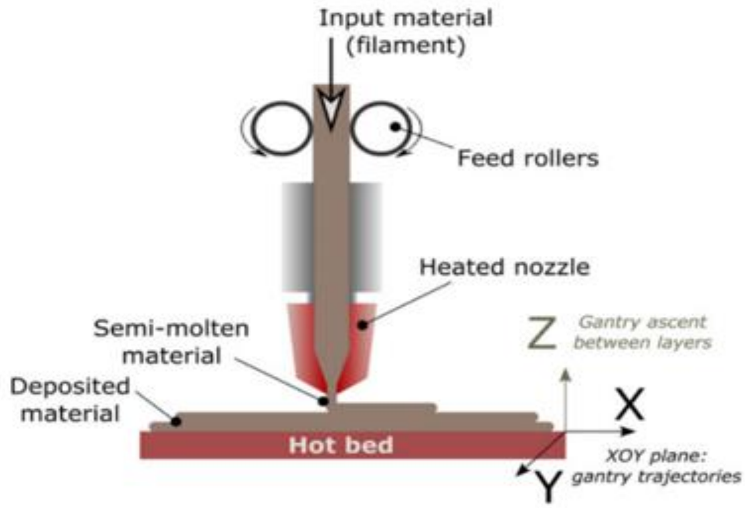


Figure 5.1. Schematic representation of FDM system (Srivastava and Rathee, 2018).

Furthermore, since FDM is required to produce high quality parts with low manufacturing cost, shorter lead time, high productivity rate, and safety concerns, the proper selection of multiple conflicting process parameters and their associated optimum conditions play an important role in not only addressing the dynamically changing customer requirements but also part quality and material properties (Groza and Shackelford, 2010; Masood, 1996). These parameter selections can also result in inverse relationships like minimal build time coupled with inferior part strength. Therefore, trade-offs must be determined based on the end use of the parts built (Ali et al., 2014). Mohamed et al. (2014) comprehensively outlined all the process variables that need be studied and optimized in an FDM process as shown in Figure 5.2.

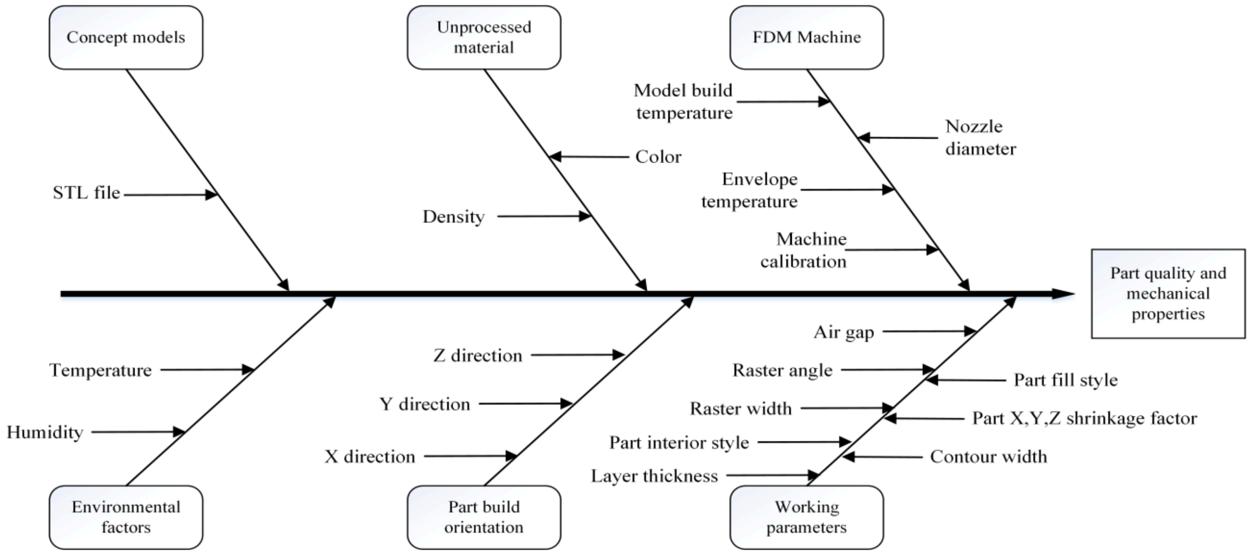


Figure 5.2. Cause and effect diagram of FDM process parameters (Mohamed et al., 2014).

In addition, it is evident that optimization of the process parameters of FDM is one the most critical design tasks to attain high quality and enhanced properties. Since, many FDM machines are available in the market, each has its own process parameter settings and effect on the associated quality characteristics of the part produced. Taguchi DOE has been the most successfully used method which can determine the best combinations of levels of process variables and interaction effects (Peace, 1993). It is not only simple, effective and reliable for reducing cost and improving quality, but also reduces the number of experiments significantly compared to other DOE methods (Roy, 2010). Although quality characteristics like tensile strength, ductility, dimensional accuracy, surface roughness, production time, etc. are the most important concerns, but there are still no optimal conditions for all types of materials and parts as there is always a need to adjust the settings.

The results from Chapter 4 also categorized the most significant parameters for the machine and the material to aid in decision making. For instance, for the FDM machine (see Table 4.6), the significant parameters were printing time (26.9%), the geometrical accuracy (20.2%) and the layer height (14.7%) while for the material, compression force acceptable for a given displacement (60%), the material being used (16%) and the surface roughness (12%) were the important concerns (embedded in results of Table 4.5).

Therefore, the objective was to identify and optimize the FDM process parameters that influence the part strength and ensure quick delivery to the customer of the drilling grid. The problem is already defined in the start of Chapter 4. So, based on a current section-centric methodology (see Figure 5.3), two experiments were designed: each to maximize the compressive strength and lessen the time for delivery by manufacturing the part with two different materials and on two different machines.

The 1st DOE was conducted using polylactide (PLA) material on MakerBot Replicator 2X FDM machine and 2nd DOE was performed using polyethylene terephthalate glycol-modified (PETG) material on Open Edge HDE machine. This helped in choosing the right material and machine settings for building the drilling grid. Moreover, the methodology is ‘generic’ in nature and can be used to optimize various design criteria. It also has the flexibility to modify the process parameters and the relevant settings if the results are not as per the functional specifications.

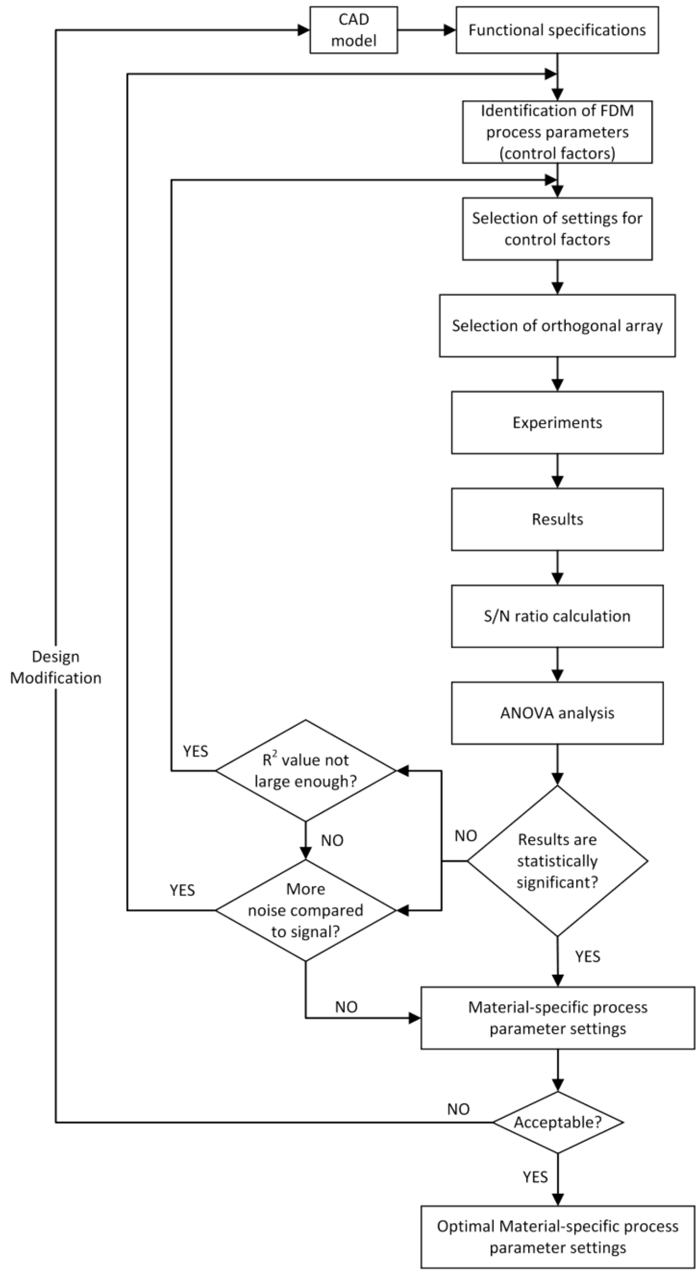


Figure 5.3. Proposed methodology – FDM process optimization using Taguchi DOE.

5.1 Identification of process parameters and relevant settings

The procedure starts with the identification of process parameters (control factors) using the extracted functional specifications (see Table 4.1) from the CAD model. Moreover, not all the parameters (see Figure 5.2) influence the strength and printing time characteristics. Therefore, based on the most recent literature (Anita et al., 2001; Dong et al., 2018; Lee et al., 2005; Percoco et al., 2012; Rangisetty, 2017; Sood et al., 2012; Wang et al., 2007; Zhang and Peng, 2012), the concerned 'working parameters' are listed in Table 5.1.

Sr. No.	Working Parameter	Unit	Description
1	Layer thickness	mm	Minimum layer thickness achieved during part build
2	Shells	-	Number of layers on the outside of a print
3	Infill pattern	-	Pattern the nozzle is drawing to fill the object
4	Infill percentage	%	Percentage of the object's volume (inside) that is filled with material

Table 5.1. FDM process parameters used in the proposed methodology (Figure 5.3).

It then specifies the levels (settings) of the control factors that need to be optimized. To assess the levels for each process parameter, the ranges of each parameter in the FDM machine are analysed as per the process knowledge/experience. Since, it is important to select the right level values for the chosen control factors in DOE, the number of levels of each factor depends on the behaviour of response variable (e.g. compressive strength) to the factor under consideration (Chockalingam et al., 2006). The levels set for the parameters for the 1st and 2nd DOE are listed in Table 5.2.

Sr. No.	Control factors	Unit	Level 1 (L1)	Level 2 (L2)
1	Layer thickness (A)	mm	0.3	0.2
2	Shells (B)	-	2	4
3	Infill pattern (C)	-	linear	diagonal
4	Infill percentage (D)	%	30	70

Table 5.2. Levels (settings) of process parameters for 1st and 2nd DOE.

5.2 Selection of Orthogonal Array (OA)

Based on the control factors and the settings chosen, suitable Taguchi's orthogonal array (OA) is devised. The selection of a specific OA is based on the number of factors, the levels for each factor and the interactions between them. The OA for both DOEs is listed in Table 5.3. It is assumed that there is no interaction between the control factors.

Experiment No.	Control Factors			
	Layer Thickness (A)	Shells (B)	Infill pattern (C)	Infill percentage (D)
1	1	1	1	1
2	1	1	1	2
3	1	2	2	1
4	1	2	2	2
5	2	1	2	1
6	2	1	2	2
7	2	2	1	1
8	2	2	1	2

Table 5.3. Orthogonal array (L_8) for 1st and 2nd DOE.

5.3 Experiments

The proposed model for output (Y) for both experiments was depicted by Equation 1.

$$\boldsymbol{Y = m + A + B + C + D} \quad (1)$$

where *m* is the mean value of all the experiments (for a given output) and *A*, *B*, *C* and *D* are the control factors. One of the manufactured samples for the drilling grid in 1st and 2nd DOE is shown in Figure 5.4.

(a) (b)

Figure 5.4. One of the 8 samples of drilling grid printed in (a) 1st DOE and (b) 2nd DOE.

For both DOEs, as stated before, OAs of L8 were chosen, i.e., 8 experiments were undertaken each time to produce drilling grids with PLA on MakerBot Replicator 2X FDM machine (1st DOE) and PETG material on Open Edge HDE machine (2nd DOE), respectively. The specifications of the FDM machine in 1st DOE and 2nd DOE are listed in Table 5.4. The other fixed parameters include printing speed of 90 mm/s, extruder temperature of 210°C and heated build surface of 25°C. Once the parts were built with each experiment, compression tests were conducted for all the 16 samples (8 for each experiment) for a given displacement of 3 mm with an impression speed of 1 mm/min (ASTM, 2015) for each sample.

Machine Parameters	**1st DOE**	**2nd DOE**
	MakerBot Replicator 2X	**Open Edge HDE**
Build volume	246 mm x 152 mm x 155 mm	300 mm x 200 mm x 200 mm
Layer resolution	100 µm	100 µm
Filament diameter	1.75 mm	1.75 mm
Nozzle diameter	0.4 mm	0.4 mm
XY positioning precision	11 µm	250 µm
Z positioning precision	2.5 µm	6.25 µm

Table 5.4. FDM machine specifications for 1st and 2nd DOE

5.4 Signal-to-noise (S/N) ratio calculation and Analysis of Variance (ANOVA)

S/N ratio is used to determine the robustness of a design where 'signal' represents the desired value (higher compressive strength and lower printing time) while 'noise' shows the undesirable value. S/N ratio is calculated by Equation 2 (Montgomery, 2001) to maximize the output.

$$\boldsymbol{\eta = -10\ log_{10} \frac{1}{n}\left(\sum_{i=1}^{n} \frac{1}{y_i^2}\right)} \qquad (2)$$

where η is the average S/N ratio, n is the number of experiments conducted at level i, and y_i is the measured value (Y). As the objective is to maximize the compression force, the 'larger-the-better' characteristic is used.

ANOVA is applied to the results by squaring the dispersion of specific numbers. It uses a p-value that can determine the significant parameters which influence the response as well as the percentage contribution of the error. Regression analysis is also performed to verify the quality of the model chosen (see Equation 1).

5.5 Results and Discussion

As stated earlier, two experiments were designed to manufacture a drilling grid so that the compression force is maximized. For each experiment, a different material and machine was considered but the control factors and the settings (see Table 5.2) were kept the same. For the ease of understanding, the results for both experiments are displayed together along with the discussion.

The results for the 1st and 2nd DOE are shown in Table 5.5. The data was analysed using Minitab-17 software.

				1st DOE		2nd DOE	
Layer thickness (mm)	**Shells**	**Infill pattern**	**Infill percentage (%)**	**Response, Compression Force (N)**	**Printing Time (min)**	**Response, Compression Force (N)**	**Printing Time (min)**
0.3	2	linear	30	2650	71	2400	84
0.3	2	linear	70	5750	97	4700	235
0.3	4	diagonal	30	5100	81	4400	129
0.3	4	diagonal	70	6550	105	6500	233
0.2	2	diagonal	30	4400	103	3500	153
0.2	2	diagonal	70	6850	150	7100	286
0.2	4	linear	30	5250	115	3200	118
0.2	4	linear	70	7150	150	6800	179

Table 5.5. Taguchi's L8 OA for 4 process parameters each at 2 levels for 1st and 2nd DOE

ANOVA and S/N ratio analysis were also conducted to identify the optimum combination of process parameters, the results of which are displayed in Table 5.6.

		1st DOE				2nd DOE			
FDM parameters	**Symbol**	**L1**	**L2**	**Δ**	**Rank**	**L1**	**L2**	**Δ**	**Rank**
Layer thickness	A	73.53	75.27	1.74	3	72.54	73.66	1.12	4
Shells	B	73.31	75.49	2.18	2	72.24	73.97	1.73	3
Infill pattern	C	73.79	75.01	1.22	4	71.95	74.26	2.31	2
Infill percentage	D	72.47	76.33	3.86	1	70.36	75.84	5.48	1

Δ = difference between L2 and L1

Table 5.6. S/N response table for the compression force (Y) for 1st and 2nd DOE

The results from Table 5.6 conclude that compression force is affected most by infill percentage for both PLA- and PETG-based drilling grids. It is followed by number of shells, layer thickness, and infill pattern for PLA drilling grid; and by infill pattern, number of shells and layer thickness for PETG drilling grid. The main effects plots for means and S/N ratio for both DOEs are shown in Figure 5.5 and Figure 5.6, respectively.

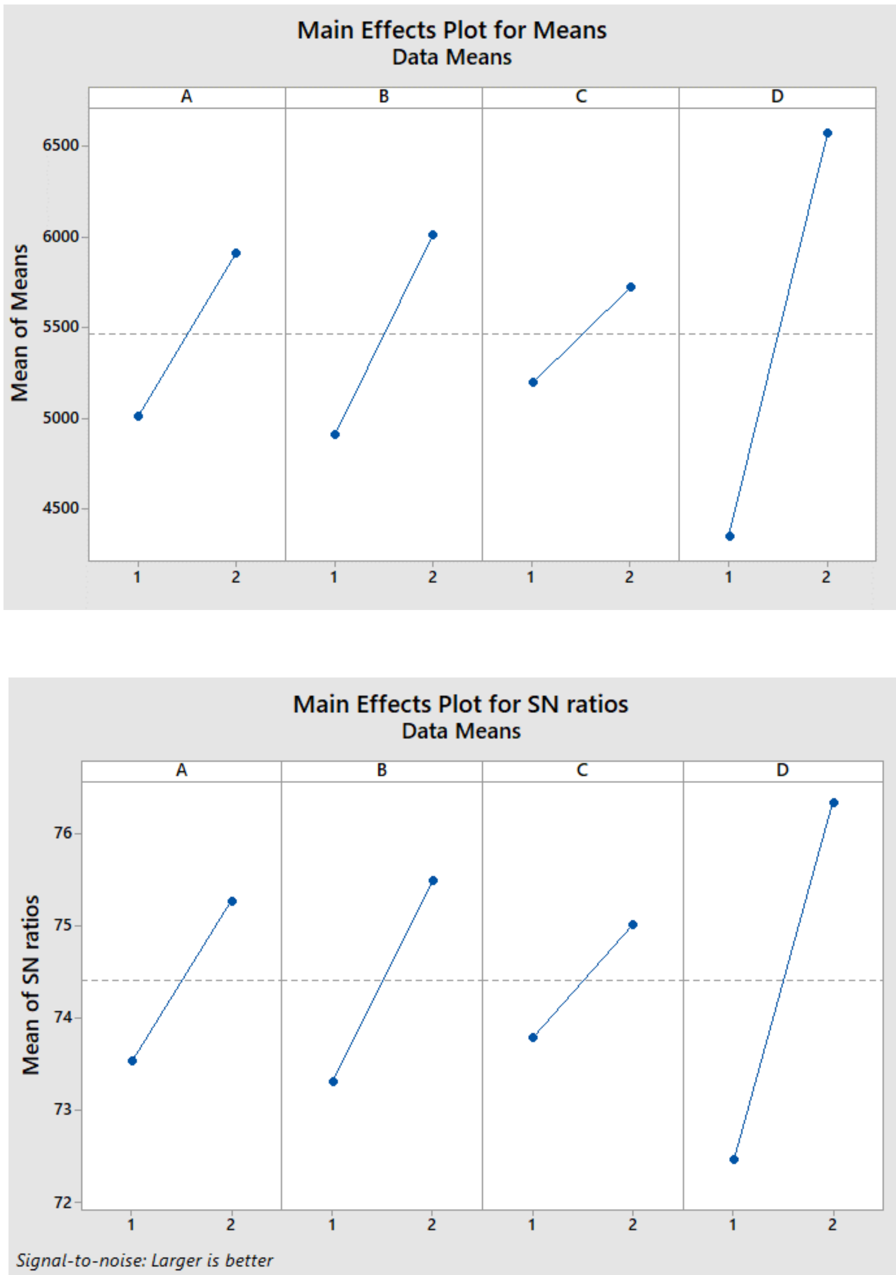


Figure 5.5. Main effect plot for means and S/N ratio for 1st DOE

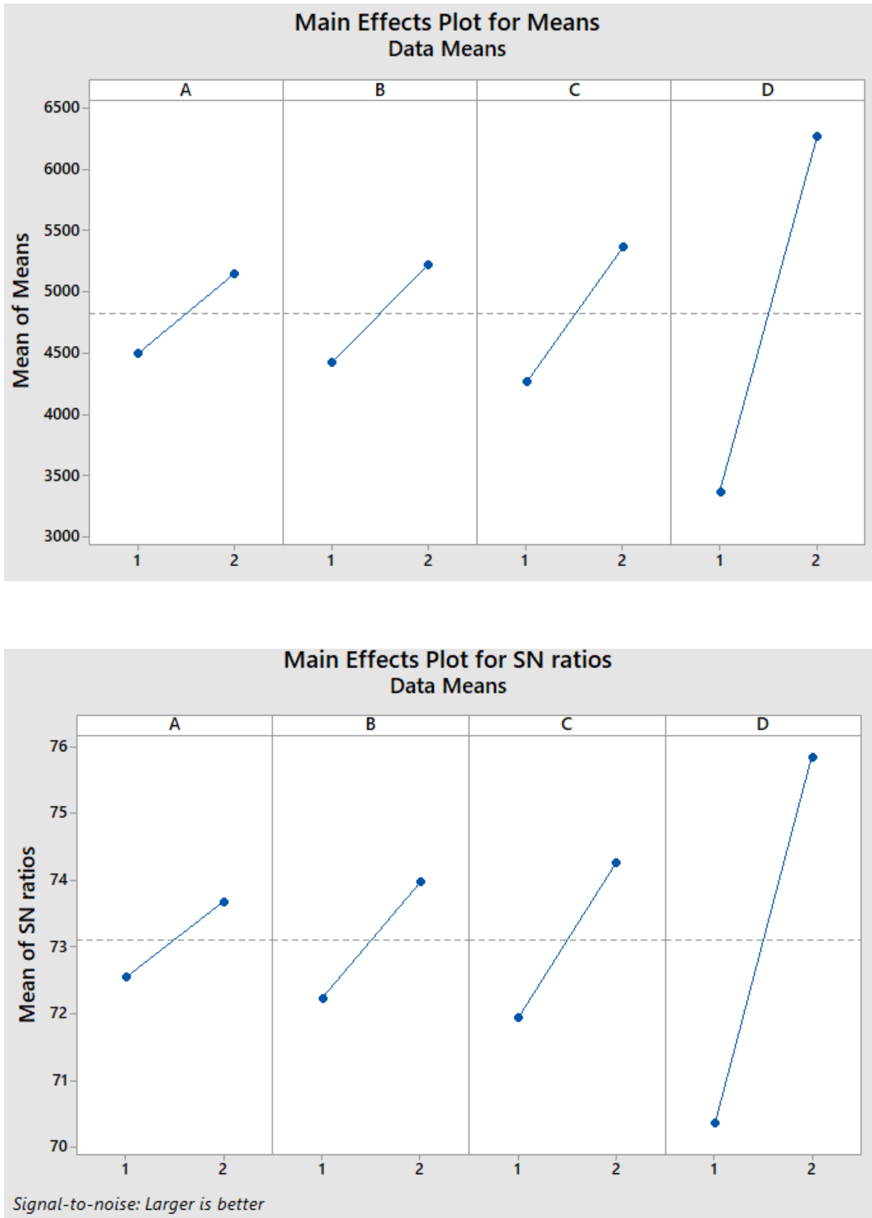


Figure 5.6. Main effect plot for means and S/N ratio for 2nd DOE

So, the combined analysis of Table 5.6 and Figures 5.5 and 5.6 shows that the combination of $A_2B_2C_2D_2$ for both DOEs, i.e., layer thickness (A) of 0.2 mm, number of shells (B) as 4, infill pattern (C) of diagonal, and infill percentage (D) of 70%, were observed as the optimum parameters to reach optimal compression force. In addition, Figures 5.5 and 5.6 show that as layer thickness decreases from level 1 (0.3 mm) to level 2 (0.2 mm), the compression force increases. Similarly, compression force increases when number of shells increase from level 1 (2) to level 2

(4) and when infill percentage increases from level 1 (30%) to level 2 (70%).

The ANOVA analysis of the results showed that the model revealed sufficiently large R^2 values for both DOEs as shown in Table 5.7. The 2nd DOE has a greater adjusted R^2 value making the results for PETG-based drilling grid comparatively better than PLA-based drilling grid.

	1st DOE			**2nd DOE**		
	R^2	**Adjusted R^2**	**Predicted R^2**	**R^2**	**Adjusted R^2**	**Predicted R^2**
Compression force	95.01%	88.36%	64.51%	95.57%	89.67%	68.51%

Table 5.7. Details of the ANOVA model for compression force for 1st and 2nd DOE

The results of the ANOVA analysis are also listed in Table 5.8 and Table 5.9 for each of the DOEs. It is found that layer thickness, number of shells and infill percentage have a significant effect on compression force for PLA built drilling grid, whereas infill pattern and infill percentage have a significant effect on compression force for PETG drilling grid as shown by the p-values which less than 0.05.

Variation source	**Df**	**Sum of squares (SS)**	**Mean square (MS)**	**F-ratio**	**p-value**
Layer thickness	1	1620000	1620000	6.38	0.086
Shells	1	2420000	2420000	9.54	0.054
Infill pattern	1	551250	551250	2.17	0.237
Infill percentage	1	9901250	9901250	39.02	0.005
Error	3	761250	253750		
Total	7	15253750			

Df = degrees of freedom

Table 5.8. Results of ANOVA for compression force (Y) for 1st DOE

Variation source	**Df**	**Sum of squares (SS)**	**Mean square (MS)**	**F-ratio**	**p-value**
Layer thickness	1	845000	845000	2.56	0.208
Shells	1	1280000	1280000	3.88	0.144
Infill pattern	1	2420000	2420000	7.33	0.073
Infill percentage	1	16820000	16820000	50.97	0.004
Error	3	990000	330000		
Total	7	22355000			

Df = degrees of freedom

Table 5.9. Results of ANOVA for compression force (Y) for 2nd DOE

It is imperative here to understand the cause for infill pattern to be not significant in case of 1st DOE. In case of PLA, infill pattern doesn't have a very strong effect on warping. It is true that warping will occur but in the case of 1st DOE, it occurs in many small areas (due to good design of part) where it doesn't matter. In addition, the linear and diagonal patterns are comparable in terms of strength. Although, linear pattern is around 10% stronger than diagonal pattern, but it has a wide error bar. Moreover, diagonal pattern (linear at 45 degrees) allows the stresses in the crossed layer to be in indirect tension and shear in a balanced way between the layers thereby providing brittle materials with an added benefit for using such pattern. This can also be seen in the 2nd DOE where infill pattern is second most important control factor impacting compressive strength. However, number of shells and layer thickness didn't significantly impact the compression force in the 2nd DOE because for PETG, different layers stick less together compared to PLA. Also, PETG is sticky during 3D printing, which makes it unsuitable for printing media but offers good adhesion of the layers. This adhesion further reinstates why the layer thickness is less important as the part is more homogeneous. It not only has good adhesion to the printing surface but also good inter-layer strength. Moreover, the limited viscosity of PETG doesn't allow all gaps to be filled in thick layers. Therefore, for the settings chosen in the DOE, the effect wasn't substantial. A good recommendation can be to use layer thickness below 0.2 mm. The same hypothesis goes for number of shells.

Further, the printing time was logged for reference in Table 5.5 to show that the printing time as per the proposed methodology of both drilling grids is well below the industrial standard of 24 hours for design, manufacture and delivery of drilling grids. This is an added benefit along with the maximization of compressive strength.

5.6 Conclusion

This section provided a generic methodology to optimize the process parameters related to one of the selected AM processes, i.e., FDM. The experimental setup and proposed section-centric methodology (Figure 5.3) can be successfully incorporated as part of the integrated product-process design (IPPD) methodology (Figure 3.1) wherein it is necessary to simultaneously consider the customer requirements, manufacturing constraints, the available AM materials, and the corresponding AM manufacturing processes. Moreover, since multiple design criteria can be added to this DOE-based methodology, it can be used for obtaining optimal settings for various process parameters for multiple objectives. It will also help in capturing the design requirements and structuring the design knowledge for an embodiment that satisfies the floated need by exploring the DfAM guidelines, constraints, fundamental scientific principles and associated relations (Zaman et al., 2018b). The looping back procedure of Figure 5.3 can also help in re-design of the part if the generated process parameter settings are not acceptable.

Section 4

Research Conclusions

Chapter 6: Conclusion and Perspectives

6.1 Conclusion

IPPD is a collaborative product development effort which takes inspiration from CE and provides output in the form of reduced costs, increased functional performance, and sustainability. Since 70–80% of the cost is incurred due to the manufacturability of the part, it is necessary to provide flexibility to change process parameters early in the design phase. Moreover, as there are numerous materials available today with various manufacturing processes, it is imperative to select the best compromised recipe for making a part in terms of MPS. Therefore, there was a need to develop a generic methodology that can consider all areas of application (e.g., aerospace, automotive, health care) for various design criteria such as function, cost, and environment. The methodology should also be able to take in to account the available DfAM guidelines to generate the requirements and attributes to manufacture a part.

Therefore, a generic decision methodology, based on Ashby's material selection charts and MCDM, was presented in this doctoral research to suggest the best compromise of material(s), manufacturing process(es) and machine(s) for AM technology. The proposed methodology can also be used easily as a guideline for researchers in the field of IPPD to provide first-hand information related to AM MPS for all areas of application. The study was a thorough design task and worked intensively in the conceptual and embodiment design stages. It employed step by step and easy to implement procedures in conjunction with the DfAM guidelines, application type, functional constraints, and part requirements to generate material and machine combinations for a given AM manufacturing process(es) using two different MCDM methods; AHP and SAW. Both methods helped to validate the proposed methodology. An AM machine database of 134 renowned machines from 38 international vendors along with AM-specific materials' database was also used to provide the most feasible MPS.

Standard translation, screening and ranking procedures governed the steps followed in the methodology. 'Translation' involved evaluation of design criteria considering the functional requirements, available cost data, and environmental impact and generating the product and/or process requirements. The second step 'screened' the relevant material classes and manufacturing processes, and the third step 'ranked' the alternatives available to help in final MPS based on subjective and objective weights. The subjective weights were used when the areas of application along with the design criteria were considered, while objective weights were associated to each of the sub-criteria. The objective weights are application-area specific and are governed by the assigned global priorities.

Moreover, the scope of the methodology doesn't end here as it can be expanded to include multiple design criteria with both dependent and independent design attributes. The splitting of parameters into two groups, i.e. machine-related and material-related, also provided an in-depth opportunity to study each parameter in detail with respect to its associated design criteria. Finally, the generated AM materials and machines with respect to the chosen AM process provided enough opportunity for the consumer to try multiple combinations as per constraining factors such as budget.

An industrial case study from the aerospace industry was used to validate the methodology. It was based on a 'drilling grid' which is used to drill holes on the sides of an aircraft body with accuracy and precision. The machine, Fortus 900 mc, running on AM process 'FDM' was chosen to manufacture the part. The machine can use any of Nylon 6, ULTEM 1010, PC, PC ISO and PPSF/PPSU as the build materials. The materials were ranked as well with each assigned a score based on the material attributes defined for AHP.

In addition, as optimization of process parameters is one of the most critical design tasks, a chapter-centric generic methodology was proposed in Chapter 4 to optimize the process parameters related to one of the AM technologies, i.e., FDM to attain high quality and enhanced properties. FDM was chosen for Taguchi's DOE as the theoretical validation (Chapter 3) selected it to manufacture the drilling grid. The experimental setup and proposed methodology can be successfully incorporated as part of the global IPPD methodology (Figure 3.1) as well. Moreover, since multiple design criteria can be added to the DOE-based methodology, it can be used for obtaining optimal settings for various process parameters for multiple objectives. It will also help in capturing the design requirements and structuring the design knowledge for an embodiment that satisfies the floated need by exploring the DfAM guidelines, constraints, fundamental scientific principles and associated relations (Zaman et al., 2018b). The looping back procedure can also help in re-design of the part if the generated process parameter settings are not acceptable. The work can be extended to other intricate CAD models as well by increasing the number of output variables.

Two experiments were designed to manufacture the drilling grid so that the compression force was maximized. The FDM process parameters: layer thickness, number of shells, infill pattern and infill percentage, were considered along with two levels of settings. The optimal combination of process parameters was suggested with each experiment having a different material and machine. The results of main effects, S/N ratio and ANOVA revealed that layer thickness, number of shells and infill percentage had a significant effect on compression force for PLA-drilling grid (1^{st} DOE), whereas, infill pattern and infill percentage had a significant effect on compression force for PETG-drilling grid (2^{nd} DOE).

To summarize, AM not only has the potential to build anything, but also carries the capability to implement it as well. Therefore, it has become essential to simultaneously address both the product and process data for effective MPS, keeping in view various design criteria, attributes, functionality constraints and areas of application to act truly as a disruptive technology for both the consumer and manufacturer.

6.2 Perspectives

The subject thesis focused on formulating a global approach to select compromised material(s) and manufacturing process(es) for a selected AM technology by considering the DfAM guidelines, areas of application, design criteria for the part, and manufacturing constraints. It also assessed the impact of selected AM process parameters on maximizing or minimizing a design objective via a generic sub-methodology which is embedded in the global approach (Figure 3.1). However, given the fact that the industry today is inclined toward CE and Industry 4.0, the following are the potential areas / perspectives related to the current work which can be worked upon in future:

1. For a product in focus, there are always two outlooks involved; one, related to the designer, and the other related to the manufacturer. With the designer's perspective, design criteria such as function, cost, and environment have more weight than the process data. More focus is similarly given to optimization of the topology, shape, size, and micro-level enhancements of the part as discussed in the literature reviewed. This has grabbed a lot of attention from MOO domain as their methods suite the designer's perspective more. But, as we move to the manufacturer's perspective, the element of "pick and choose," i.e., MCDM methods, comes into consideration. With a large solution space available with various materials and manufacturing processes, a manufacturer works in two distinct domains: one, where materials and their respective properties have a strong influence on product design and processing capabilities, and two, where finite set of materials and manufacturing processes restrict the luxury of design modifications too often. Therefore, a generic global optimization tool needs to be structured that can bridge the gap between product and process data by not only working on the available knowledge systems but also considering both the product and process data individually. If there are varying objectives, combination of dependent and independent attributes and many functional requirements, a combination of MCDM and MOO methods need to be undertaken. For the individual consideration, local optimization tools can be designed which can evaluate the impact of various product parameters on the final product as well as the sub-parts.

2. Autonomous and interlinked manufacturing systems that can self-organize the production of small batch sizes to lot size 1, is the vision of Industry 4.0. To realize this vision, new design

paradigms in manufacturing system design are necessary such as the concept of a 'Digital Twin'. A digital twin is defined as the digital representation of a unique asset (machine, product, service, product service system or other intangible asset), that alters its properties, condition and behaviour by means of models, information and data (Stark, Kind, & Neumeyer, 2017). With respect to the current work of the thesis, the databases (related to materials and machines), product and process information, and the functional/non-functional requirements can be stored in an integrated model that can act as an evolving digital profile that can record current and historical behaviour of product/process and help in optimizing business performance. Figure 6.1 shows how a manufacturing process in the physical world is replicated in the digital world as a twin:

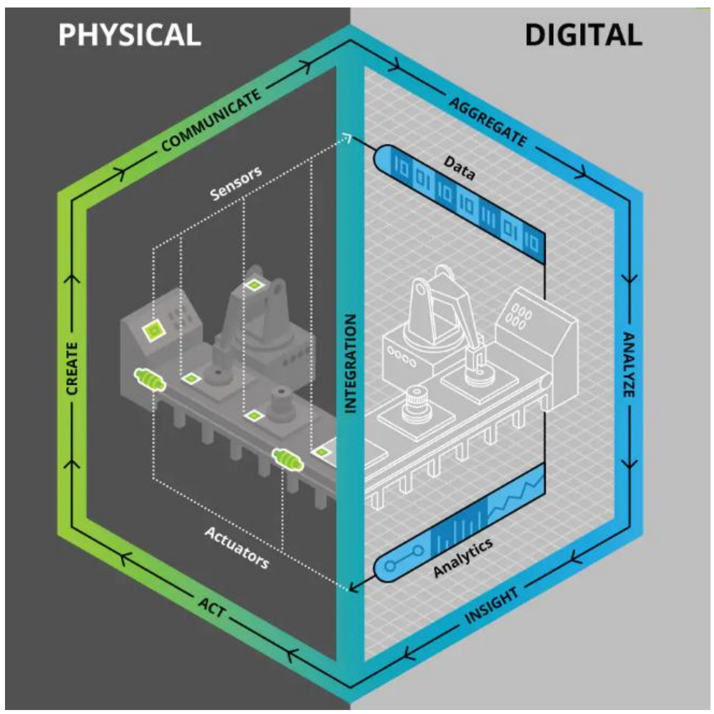


Figure 6.1. Conception of a digital twin (Parrot and Warshaw, 2017)

The 'data' in the above figure can be obtained from the databases structured and the product/process information generated (CAD drawings, functional specifications, product-process requirements, Ashby's material selection charts, etc.) in the subject thesis. The information can be analysed in the 'analytics' section using algorithmic simulations. As digital twins provide a near to real-time linkage between the digital and physical worlds, they can provide more realistic and holistic measurements of unpredictability[5]. Predictive model can therefore, be embedded within the integrated model to identify the problems in advance such as related to manufacturing quality, state of the AM machine, etc.

3. A global framework can be worked upon to embed the current approach of the thesis in the framework of hybrid manufacturing wherein AM and TM processes can be collectively used. However, as discussed in literature review (Figure 2.5), the suitable results appear if the TM processes are used downstream of the process chain. TM processes can further improve the outlook of the part and help in achieving functional specifications and reducing the cost and printing time by minimizing the avenues for re-design of the part if the specifications are not satisfied.

4. As manufacturing these days is becoming more complex and integrated, it is being pressurized by more cost and environmental impact reductions. Cloud manufacturing (CM) can handle such situations by undertaking intelligent decisions to provide the most robust and sustainable manufacturing route for a process (Fisher et al., 2018). Collaborative design, improved process resilience, greater automation, and enhanced waste reduction, reuse and recovery, are few of the many advantages associated with CM. The CM platform interconnects the manufacturing capabilities (design, fabrication, assembly, testing, etc.), manufacturing resources (AM machines, tools, CAD/CAM/CAE/CAPP softwares), and models (repositories, databases) to form a shared pool (Ren et al., 2015) which can not only provide intelligent solutions to the personalized requirements and customized needs, but also create an agile manufacturing model that can virtualize manufacturing resources and capabilities and transform them into on-demand services that are available to the users throughout the product lifecycle (Zhang et al., 2014). The IPPD framework proposed in this thesis can be integrated within the CM platform to include factors such as supply chain. The constraints of production can be integrated with various other factors such as AM machines available in the facility, facility layout, etc. The freedom to change the machine and material attributes and the optimization of the AM process parameters with respect to change in design of the part/process, are few of the many notable advantages of the thesis methodology being embedded in the framework of CM.

To sum up, with new emerging technologies such as AM, it has become essential to

[5] https://www2.deloitte.com/insights/us/en/focus/industry-4-0/digital-twin-technology-smart-factory.html

simultaneously address both the product and process data for effective MPS. Various design criteria and areas of application can make IPPD systems as futuristic machines bringing value to both consumer and manufacturer. Industry 4.0 has opened new avenues for the digital world to mesh with the manufacturing paradigms and bring new levels of production success. With the perspectives discussed in the current section, the IPPD-based methodology proposed in the current thesis can bring new and improved research contributions to the scientific world.

ANNEXURES

Annexure A
Portion of Material Database

Material Class	Material	Process	YSmin	YSmax	TSmin	TSmax	Duct Min	Duct Max	Ks	Kr	Density	Mat cost/ kg	SF Min	SF Max	MU E	Env Imp	Land Waste
Metals	Ti-6Al-4V	LENS	1022	1022	923	923	11	11	1	1	0.00000442000	220	6.00	12.00	100	Equal	Equal
Metals	316 SS	LENS	500	500	799	799	50	50	1	1	0.00000800000	6	8.00	18.00	100	Equal	Equal
Metals	304 SS	LENS	503	503	717	717	51	51	1	1	0.00000800000	6	1.89	5.90	100	Equal	Equal
Metals	IN 718	LENS	1117	1117	1393	1393	16	16	1	1	0.00000820000	120	4.00	6.50	100	Equal	Equal
Metals	IN 625	LENS	584	584	938	938	38	38	1	1	0.00000844000	100	4.00	6.50	100	Equal	Equal
Metals	Ti-6Al-4V	SLM	980	1020	1030	1070	10	10	1	1	0.00000442000	220	6.00	13.70	100	Equal	Equal
Metals	316 SS	SLM	662	662	686	686	31	31	1	1	0.00000800000	6	8.00	18.00	100	Equal	Equal
Metals	316L SS	SLM	513	523	660	664	37	39	1	1	0.00000800000	13	8.00	18.00	100	Equal	Equal
Metals	304 SS	SLM	538	538	700	700	37	37	1	1	0.00000800000	6	1.89	5.90	100	Equal	Equal
Metals	17-4 PH SS	SLM	490	590	1000	1100	20	30	1	1	0.00000778000	13	2.50	4.50	100	Equal	Equal
Metals	AlSi10Mg	SLM	232	248	385	397	5	6	1	1	0.00000267000	20	6.00	10.00	100	Equal	Equal
Metals	Ti-6Al-4V	EBM	950	950	1020	1020	14	14	1	1	0.00000442000	220	31.10	31.10	100	Equal	Equal
Metals	Ti-6Al-4V	LMD	1060	1060	1160	1160	6	6	1	1	0.00000442000	220	0.70	13.30	100	Equal	Equal
Metals	420 SS (60% SS, 40% Bronze)	3DP	427	427	496	496	7	7	1	1	0.00000780000	13	1.25	15.00	100	Equal	Equal
Metals	316 SS (60% SS, 40% Bronze)	3DP	283	283	580	580	15	15	1	1	0.00000800000	6	1.25	15.00	100	Equal	Equal
Polymer	ABS-M30	FDM	2230	2230	32	32	7	7	1	1	0.00000104000	350	40.00	600.00	100	Equal	Equal
Polymer	ABSi	FDM	1920	1920	37	37	4	4	1	1	0.00000108000	350	40.00	600.00	100	Equal	Equal
Polymer	PCABS	FDM	1810	1810	41	41	5	5	1	1	0.00000120000	395	40.00	600.00	100	Equal	Equal
Polymer	ULTEM 9085	FDM	2150	2150	69	69	6	6	1	1	0.00000134000	454	18.76	18.76	100	Equal	Equal
Polymer	ULTEM 1010	FDM	2770	2770	81	81	3	3	1	1	0.00000127000	454	10.00	10.00	100	Equal	Equal
Polymer	ABS Plus	FDM	2200	2200	33	33	6	6	1	1	0.00000105000	260	40.00	600.00	100	Equal	Equal
Polymer	PPSF	FDM	2068	2068	55	55	3	3	1	1	0.00000128000	454	11.44	11.44	100	Equal	Equal
Polymer	VisiJet M2 RWT	MJP	1000	1600	37	47	7	16	1	1	0.00000119000	348	15.00	15.00	100	Equal	Equal
Polymer	VisiJet M2 RBK	MJP	600	1100	29	37	11	21	1	1	0.00000112000	348	15.00	15.00	100	Equal	Equal

Polymer	VisiJet M2 RCL (PC-like)	MJP	1000	1600	40	50	9	18	1	1	0.00000118000	348	15.00	15.00	100	Equal	Equal
Polymer	VisiJet M5-X (ABS/PP)	MJP	1925	1925	39	39	8	8	1	1	0.00000102000	351	1.82	1.82	100	Equal	Equal
Polymer	VisiJet M5 Black	MJP	1555	1555	33	33	15	15	1	1	0.00000102000	351	1.82	1.82	100	Equal	Equal
Polymer	RGD 430	MJP	1000	2000	20	30	40	50	1	1	0.00000116000	325	40.00	600.00	100	Equal	Equal
Polymer	RGD 875 (VeroBlackPlus)	MJP	2700	2700	58	58	10	25	1	1	0.00000118000	300	16.00	16.00	100	Equal	Equal
Polymer	R5 Gray	DLP	1960	1960	50	50	5	5	1	1	0.00000122000	339	3.35	3.35	100	Equal	Equal
Polymer	R11	DLP	75	75	50	50	8	8	1	1	0.00000122000	339	3.35	3.35	100	Equal	Equal
Polymer	RCP 30	DLP	102	102	46	46	3	3	1	1	0.00000120000	339	3.35	3.35	100	Equal	Equal
Polymer	RC 90	DLP	104	104	38	38	3	3	1	1	0.00000120000	339	3.35	3.35	100	Equal	Equal

Description of nomenclature used

Sr. No.	Index	Unit	Description
1	YSMin / YSMax	MPa	Minimum and Maximum Yield strength
2	TSMin / TSMax	MPa	Minimum and Maximum Tensile strength
3	DuctMin / DuctMax	%	Minimum and Maximum Ductility at Break
4	SFMin / SFMax	µm	Minimum and Maximum Surface finish
5	Matcost/kg	US$/kg	Material cost per kilogram
6	MUE	%	Material usage efficiency
7	EnvImp	-	Environmental Impact
8	LandWaste	-	Landfill waste

Annexure B
Portion of Machine Database

Machine Name	Manufacturer	Process	Accu Min	Accu Max	Layer ThickMin	Layer ThickMax	Build VolX	Build VolY	Build VolZ	MachCost Min	MachCost Max	Aero	Moto	HC	CP	IA	Arch	G/M
Form1+	Formlabs	SLA	0.00	0.30	25	200	125	125	165	2603	2603	0	0	1	1	0	0	0
Form 2	Formlabs	SLA	0.30	0.30	25	100	145	145	175	3499	3499	0	0	1	1	0	0	0
CubePro HD	3D Systems	FDM	0.10	0.10	70	70	285	270	230	3830	3830	0	0	0	1	0	1	0
CubePro SD	3D Systems	FDM	0.10	0.10	200	200	285	270	230	3830	3830	0	0	0	1	0	1	0
CubePro HS	3D Systems	FDM	0.10	0.10	300	300	285	270	230	3830	3830	0	0	0	1	0	1	0
ProJet 1200	3D Systems	SLA	0.03	0.05	30	30	43	27	150	4900	4900	0	0	1	1	0	0	0
Xfab	DWS Lab	SLA	0.25	0.25	10	100	180	180	-	5500	5500	0	0	0	1	0	0	0
PICO2	Asiga	SAS	0.04	0.04	1	1	51	32	75	11250	11250	0	1	1	1	0	1	0
Freeform PRO2	Asiga	SAS	0.05	0.05	10	100	96	54	200	24990	24990	0	1	1	1	0	1	0
Fortus 250mc	Stratasys	FDM	0.24	0.24	178	330	254	254	305	45000	45000	1	1	0	1	0	0	0
Objet30 Pro (with other materials)	Stratasys	Poly jet	0.10	0.10	16	16	294	192	149	30000	30000	0	0	1	1	0	0	0
Objet30 Pro (with VeroClear)	Stratasys	Poly jet	0.20	0.20	28	28	294	192	149	30000	30000	0	0	1	1	0	0	0
Fortus 380mc	Stratasys	FDM	0.13	0.13	127	330	355	305	305	175000	175000	1	1	0	1	1	0	1
Fortus 900mc	Stratasys	FDM	0.09	0.09	178	508	914	610	914	250000	300000	1	1	0	1	1	0	1
Objet1000 Plus	Stratasys	MJP	0.08	0.60	16	16	1000	800	500	250000	300000	1	1	0	0	1	0	1
Replicator+	Makerbot	FDM	0.03	0.03	100	100	195	193	165	2499	2499	1	0	0	1	1	0	0
Replicator Z18	Makerbot	FDM	0.03	0.03	100	100	300	305	457	6499	6499	1	0	0	1	1	0	0
Up Mini 2	RepRap	FDM	0.15	0.15	100	350	120	120	120	810	810	0	0	0	1	0	1	0
N2 Plus Dual Extruder	Raise3D	FDM	0.01	0.01	10	10	305	305	610	4350	4350	0	0	0	1	0	0	0
Arke	Mcor Technologies	LOM	0.10	0.10	100	100	240	205	125	20177	20177	0	0	1	1	0	1	0

Matrix 300+	Mcor Technologies	LOM	0.10	0.10	100	190	256	175	150	10000	50000	0	0	1	1	0	1	0
SD300 Pro	Solido	LOM	0.10	0.10	168	168	160	210	135	9995	9995	0	0	0	1	0	1	0

Description of nomenclature used

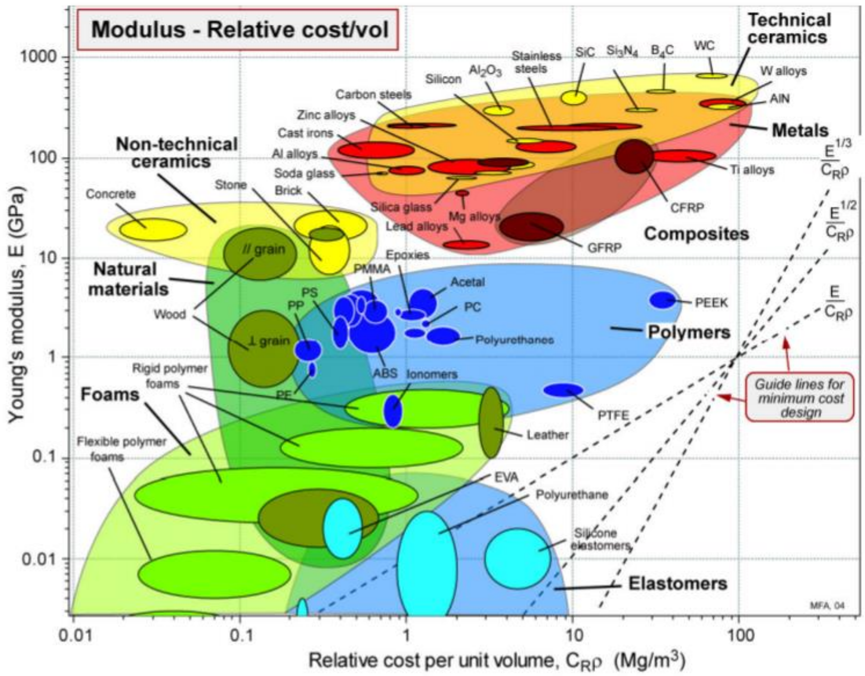
Sr. No.	Index	Unit	Description
1	AccuMin / AccuMax	mm	Minimum and Maximum Accuracy
2	LayerThickMin / LayerThickMax	µm	Minimum and Maximum Layer thickness
3	BuildVolX / BuildVolY / BuildVolZ	mm	X / Y / Z dimensions volume of build chamber
4	MachcostMin / MachcostMax	US $	Minimum and Maximum Machine cost
5	Aero / Moto / HC / CP / IA /Arch / G/M	(0 or 1)	Application areas: Aerospace / Automotive / Health care / Consumer products / Industrial applications / Architecture / Government & military

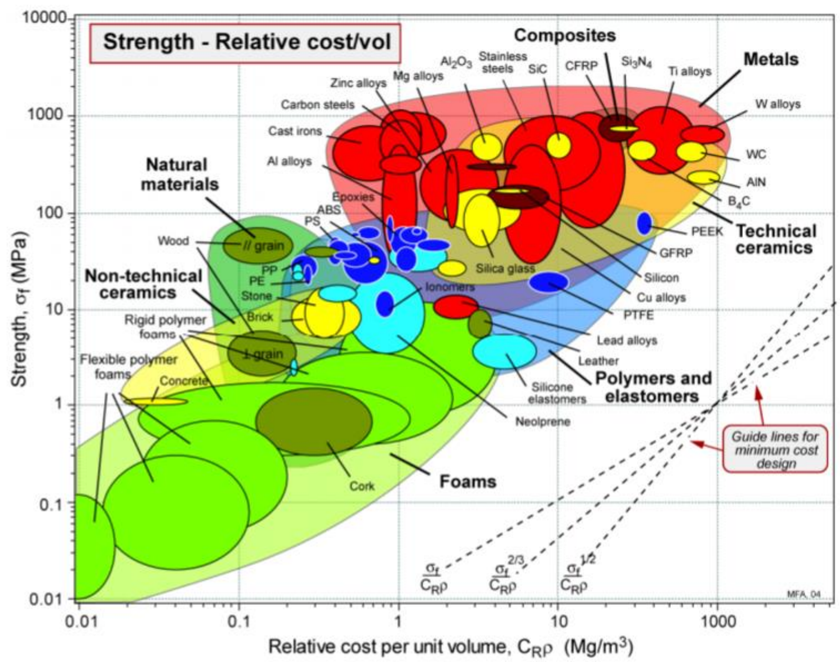
Annexure C
Process-Shape-Material Matrix for traditional and additive manufacturing processes

Material				Processes \ Shape	Circular Prismatic	Non-circular Prismatic	Flat Sheet	Dished Sheet	3D solid	3D hollow
			M	Sand Casting	✓	✓			✓	✓
			M	Die Casting	✓	✓			✓	✓
			M	Investment Casting	✓	✓			✓	✓
			M	Low pressure casting	✓	✓			✓	✓
			M	Forging	✓	✓			✓	
			M	Extrusion	✓	✓				
			M	Sheet Forming	✓	✓	✓	✓		
		Cer	M	Powder Methods	✓	✓			✓	✓
		Cer	M	Electro-machining	✓	✓	✓		✓	✓
	P	Cer	M	Conventional Machining	✓	✓	✓	✓	✓	✓
	P	Cer		Injection Molding	✓	✓			✓	✓
	P			Blow Molding				✓		✓
	P			Compression Molding			✓	✓	✓	
	P			Rotation Molding				✓		✓
	P			Thermo-forming				✓		
	P			Polymer Casting	✓	✓			✓	✓
Com	P			Resin-transfer molding	✓	✓	✓	✓	✓	✓
Com				Filament Winding	✓	✓		✓		✓
Com				Lay-up methods			✓	✓	✓	
Com				Vaccuum Bag			✓	✓		
Com	P	Cer		Stereolithography (SLA)	✓	✓	✓	✓	✓	✓
Com	P	Cer	M	Digital Light Processing (DLP)	✓	✓	✓	✓	✓	✓
Com	P	Cer	M	Multi-Jet Modeling (MJM)	✓	✓	✓	✓	✓	✓
Com	P	Cer	M	3D printing (3DP)	✓	✓	✓	✓	✓	✓
Com	P	Cer		Fused Deposition Modeling (FDM)	✓	✓	✓	✓	✓	✓
	P		M	Electron Beam Melting (EBM)	✓	✓	✓	✓	✓	✓
Com	P	Cer	M	Selective Laser Sintering (SLS)	✓	✓	✓	✓	✓	✓
Com			M	Selective Laser Melting (SLM)	✓	✓	✓	✓	✓	✓
	P		M	Direct Metal Laser Sintering (DMLS)	✓	✓	✓	✓	✓	✓
Com	P		M	Laminated Object Manufacturing (LOM)	✓	✓	✓	✓	✓	✓
			M	Ultrasonic Consolidation (UC)	✓	✓	✓	✓	✓	✓
			M	Laser Metal Deposition (LMD)	✓	✓	✓	✓	✓	✓

Index	Class
M	Metals
Cer	Ceramics
Com	Composites
P	Polymers

Annexure D
Ashby Charts (Young's modulus vs relative cost per unit volume and Strength vs relative cost per unit volume).





Annexure E
Decision matrices

	ABS -M30	ABS-ESD7	ABS i	ABS-M30i	PCAB S	ABS Plus	VisiJet M3-X	VisiJet M5-X	VisiJet CR-WT	DIGITAL ABS	ABS tuff	Plas
ABS-M30	1	1	1	1	1	1	1/4	1/4	1/4	1/4	1/6	1/4
ABS-ESD7	1	1	1	1	1	1	1/4	1/4	1/4	1/4	1/6	1/4
ABSi	1	1	1	1	1	1	1/4	1/4	1/4	1/4	1/6	1/4
ABS-M30i	1	1	1	1	1	1	1/4	1/4	1/4	1/4	1/6	1/4
PCABS	1	1	1	1	1	1	1/4	1/4	1/4	1/4	1/6	1/4
ABS Plus	1	1	1	1	1	1	1/4	1/4	1/4	1/4	1/6	1/4
VisiJet M3-X	4	4	4	4	4	4	1	1	1	1	1/4	1
VisiJet M5-X	4	4	4	4	4	4	1	1	1	1	1/4	1
VisiJet CR-WT	4	4	4	4	4	4	1	1	1	1	1/4	1
DIGITAL ABS	4	4	4	4	4	4	1	1	1	1	1/4	1
ABStuff	6	6	6	6	6	6	4	4	4	4	1	4
Plas	4	4	4	4	4	4	1	1	1	1	1/4	1

Decision matrix of the AHP for material attribute ‘surface finish’ (ABS-related)

	ABS -M30	ABS-ESD7	ABS i	ABS-M30i	PCAB S	ABS Plus	VisiJet M3-X	VisiJet M5-X	VisiJet CR-WT	DIGITAL ABS	ABS tuff	Plas
ABS-M30	1	3	2	1	6	1/5	1/4	1/3	1/4	1/2	2	5
ABS-ESD7	1/3	1	1/3	1/3	4	1/7	1/6	1/5	1/6	1/4	1/3	3
ABSi	1/2	3	1	1/2	5	1/6	1/4	1/3	1/4	1/2	1/2	4
ABS-M30i	1	3	2	1	6	1/5	1/4	1/3	1/4	1/2	1/2	5
PCABS	1/6	1/4	1/5	1/6	1	1/9	1/8	1/7	1/8	1/6	1/6	1/2
ABS Plus	5	7	6	5	9	1	2	3	2	5	6	8
VisiJet M3-X	4	6	4	4	8	1/2	1	2	2	3	4	7
VisiJet M5-X	3	5	3	3	7	1/3	1/2	1	1/2	2	3	6
VisiJet CR-WT	4	6	4	4	8	1/2	1/2	2	1	3	4	7
DIGITAL ABS	2	4	2	2	6	1/5	1/3	1/2	1/3	1	2	5
ABStuff	1/2	3	2	2	6	1/6	1/4	1/3	1/4	1/2	1	4
Plas	1/5	1/3	1/4	1/5	2	1/8	1/7	1/6	1/7	1/5	1/4	1

Decision matrix of the AHP for material attribute ‘material cost’ (ABS-related)

	ABS -M30	ABS-ESD7	ABS i	ABS-M30i	PCAB S	ABS Plus	VisiJet M3-X	VisiJet M5-X	VisiJet CR-WT	DIGITAL ABS	ABS tuff	Plas
ABS-M30	1	1	1	1	1	1	1	1	1	1	1	1
ABS-ESD7	1	1	1	1	1	1	1	1	1	1	1	1
ABSi	1	1	1	1	1	1	1	1	1	1	1	1
ABS-M30i	1	1	1	1	1	1	1	1	1	1	1	1
PCABS	1	1	1	1	1	1	1	1	1	1	1	1
ABS Plus	1	1	1	1	1	1	1	1	1	1	1	1
VisiJet M3-X	1	1	1	1	1	1	1	1	1	1	1	1
VisiJet M5-X	1	1	1	1	1	1	1	1	1	1	1	1
VisiJet CR-WT	1	1	1	1	1	1	1	1	1	1	1	1
DIGITAL ABS	1	1	1	1	1	1	1	1	1	1	1	1
ABStuff	1	1	1	1	1	1	1	1	1	1	1	1
Plas	1	1	1	1	1	1	1	1	1	1	1	1

Decision matrix of the AHP for material attributes ‘material usage efficiency’, ‘environmental impact’ and ‘landfill waste’ (ABS-related)

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Intégration Produit-Process appliquée à la sélection de procédés de Fabrication Additive

Résumé: Cette recherche vise à proposer une approche intégrée permettant la prise en compte simultanée des paramètres Produits / process dans le cadre d'une fabrication par ajout de matière. Le développement produit est en profonde mutation, prenant en compte les contraintes de personnalisation, de temps de mise sur le marché de plus en plus court, la volonté d'une approche eco-responsable etc. Ce changement de paradigme conduit à s'intéresser au choix du couple matériau /process dès la phase de conception afin de prendre en compte les contraintes liées au procédé identifié. Cette approche multi critère s'intéresse à la fois au couple matériau procédé mais prend en compte les aspect fonctionnels de la pièce. Ainsi ce travail de thèse présente une méthodologie de décision générique, basée sur des outils de prise de décision multicritères, qui peut non seulement proposer une solution satisfaisant les contraintes liées aux matériaux, processus et processus par addition de matière, mais propose également de servir de guide aux concepteurs permettant un choix raisonné basé sur des combinaisons matériau-machine orientées conception et obtenu à partir d'une base de données de 38 fournisseurs internationaux de machine de fabrication par ajout de matière.

Mots clés: fabrication additive; conception pour la fabrication additive; conception intégrée des processus de produits; sélection des matériaux et des processus; prise de décision multicritère

Integrated product-process design applied to the selection of additive manufacturing processes

Abstract: The doctoral research focuses to build an integrated approach that can simultaneously handle the product and process parameters related to additive manufacturing (AM). Since, market dynamics of today are constantly evolving, drivers such as mass customization strategies, shorter product development cycles, a large pool of materials to choose from, abundant manufacturing processes, etc., have made it essential to choose the right compromise of materials, manufacturing processes and associated machines in early stages of design considering the Design for AM guidelines. As several criteria, material attributes and process functionality requirements are involved for decision making in the industries, the thesis introduces a generic decision methodology, based on multi-criteria decision-making tools, that can not only provide a set of compromised AM materials, processes and machines but will also act as a guideline for designers to achieve a strong foothold in the AM industry by providing practical solutions containing design oriented and feasible material-machine combinations from a database of 38 renowned AM vendors in the world today.

Key words: additive manufacturing; design for additive manufacturing; integrated product process design; material and process selection; multi-criteria decision making

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