



# Méthodologie de prise de décision multicritère pour l'évaluation de la performance durable dans la conception et la fabrication des produits - Application à la fabrication additive

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**UNIVERSITE - CLERMONT FERRAND**  
Ecole Doctorale Sciences pour l'Ingénieur de Clermont Ferrand

**Thèse**

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**Spécialité: Informatique**

**Multicriteria decision making methodology for sustainability  
evaluation in the design and manufacturing of engineering  
products - Application to Additive Manufacturing**

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## Dedication

I would like to dedicate this study to my dear father, Ato Ashagrie Taddese Woldie. I was not by your side when you took your last breath and that is the most regrettable part of my life. However, I never forgot to be a man of your dreams and I am determined in every second of my life to fulfill your lifetime wish for me to be a better man.

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– Psalm 145:3**

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## Abstract

Assuring sustainability is becoming a key focus area in the current design and manufacturing of products. The emerging shift from design for manufacturing to design for additive manufacturing is a prospect for researchers and original equipment manufacturers (OEMs) to focus on sustainability of design and manufacturing of products throughout the products' life cycle. Recently, this is common in high-value aircraft components. However, the majority of past researches failed to fully achieve sustainability in manufacturing because achieving it requires balanced and exhaustive consideration of sustainability dimensions and utilization of appropriate multicriteria decision-making methodology (MCDM) in metrics selection based on the intended goal. Most research outcomes during the past decade also revealed that additive manufacturing is showing better opportunities for sustainable performance than conventional manufacturing processes. Therefore, many research outcomes recommend industries and OEMs to make informed decisions by fully understanding and taking simultaneous and balanced consideration of sustainability and its dimensions in product design and manufacturing.

The purpose of this study is to develop a comprehensive MCDM methodology for sustainability in the design and manufacturing of engineering products by taking an application of Faceshield bracket manufacturing using three processes; Injection molding, 3D printing, and Laser cutting by using Analytical Hierarchy Process (AHP). To do so, it was necessary to first assess the comprehensiveness of sustainability performance indicators (SPIs) based on a balanced consideration of all dimensions of sustainability. Then the development of a new list of SPIs which is comprehensive, exhaustive, with an appropriate interpretation that can be easily validated is supplemented. Moreover, the sustainability performance of additive manufacturing processes is assessed and finally, a methodology of MCDM is proposed to compare sustainable performance between processes used to manufacture three different types of Faceshield brackets. The whole study is organized into three parts.

The first part focused on the development of a comprehensive list of SPIs throughout the life cycle of the product. This was done through extensive literature review and analysis about requirements of sustainable products and review, describe and analyze a comprehensive list of these indicators by intensively assessing different applications, frameworks, sustainability indicators indexes, and various recommendations based on the three dimensions of sustainability (environment, economic and social). The second part focuses on analyzing the sustainability performance of additive manufacturing considering each dimension of sustainability. This has been done by focusing on the sustainability of manufacturing processes, which assesses categorization of manufacturing processes and a more detailed discussion on conventional and additive manufacturing processes. The third part of the study focuses on developing a compressive MCDM methodology by using Analytic Hierarchy Process (AHP). This

methodology is proposed to assist decision-makers in comparing the sustainability performance of the three manufacturing processes by using considering the proposed SPIs.

A total of 68 SPIs are proposed as the first outcome of this study. Among which, 29 are for the environment, 9 are for economic and 30 are for the social dimension of sustainability. Besides the proposal of these indicators, the existing level of subjectivity, product life cycle considerations, quantification, and interpretation strategy is taken into account. Secondly, comparative analysis on the sustainability performance of additive manufacturing processes is done focusing on criteria selection schemes, design modification requirements, and various factors as a selection approach. Finally, a comprehensive MCDM methodology for sustainability evaluation in the design and manufacturing of engineering products is proposed by using AHP. In the proposed comprehensive methodology, ranking of the proposed SPIs for better sustainable performance of processes considered. Faceshield bracket manufacturing using three manufacturing processes is considered as an application to validate for relevance and effectiveness of the proposed methodology.

Finally, it is recommended that decision-makers should be aware that decision-making trends depend on conflicting objectives when considering manufacturing as an integrated concept rather than just transforming raw materials into products. Moreover, structuring the problem in a hierarchy and making judgments on preference matrices must be carefully considered as this may divert the final preference.

**Keywords:** Sustainability, sustainable manufacturing, additive manufacturing, multicriteria decision-making methodology, analytic hierarchy process.

## Résumé

### Chapitre 1: Problématique de recherché

Evaluer la performance durable de la conception et de la fabrication de produits joue un rôle important pour améliorer la qualité de vie globale dans les systèmes socio-économiques actuels. Plusieurs études révèlent que les activités de fabrication représentent une charge importante sur l'environnement (Haapala et al., 2013). Les systèmes de fabrication doivent chercher un équilibre entre les objectifs économiques, environnementaux et sociaux plutôt que de se concentrer uniquement sur les avantages économiques. Il est temps d'envisager l'évolution du système de fabrication par rapport à la fabrication durable (Zhang et al., 2013), définie comme "la création de produits manufacturés qui utilisent des procédés qui minimisent les impacts négatifs sur l'environnement, conservent l'énergie et les ressources naturelles, sont sûrs pour les employés, les communautés et les consommateurs, et sont économiquement sains" (Shao et al., 2017). La fabrication durable est considérée comme une solution efficace pour soutenir la croissance et pour réduire l'impact environnemental et améliorer les performances économiques de l'industrie manufacturière.

La littérature montre qu'il existe encore des manques dans la compréhension du terme de performance durable, dans la prise en compte simultanée et équilibrée des dimensions de performance durable ainsi que dans la prise en compte des indicateurs de performance pour chaque dimension et des approches et méthodologies d'évaluation de la performance durable.

Ainsi, cette étude vise à répondre à cette problématique en proposant une liste complète des indicateurs de performance durable et une méthodologie de prise de décision multicritères qui doit comparer plusieurs critères contradictoires pour établir des priorités en fonction de l'objectif visé.

Les aspects du cycle de vie des produits sont récemment devenus des préoccupations majeures de nombreuses industries, des équipementiers et des chercheurs sur le sujet. Les contraintes de fabrication sont des défis majeurs dans la conception et le développement des produits. Leurs complexités limitent la prise en compte des trois dimensions de la performance durable dans le cycle de vie du produit. (Borchardt et al., 2011; Bovea et Pérez-Belis, 2012; Jin et al., 2017; Peralta Álvarez et al., 2017). Mais la définition de la performance durable et de la fabrication durable elle-même varie, (Haapala et al., 2013; Yuan et al., 2012). En faisant évoluer ces contraintes, la fabrication additive devrait permettre d'améliorer la performance durable des produits. Afin de saisir les possibilités offertes par ce procédé, il est nécessaire d'identifier et de comprendre la performance durable des procédés de fabrication additive par rapport aux procédés de fabrication conventionnels (Gardan et Schneider, 2015 ; Gebisa et Lemu, 2017 ;



Huang et al., 2013 ; Jared et al., 2017 ; Nathan, 2015 ; Sossou et al., 2018 ; Tang et al., 2016 ; Thompson et al., 2016 ; Bikas et al., 2016 ; Bourell et al., 2017 ; Frazier, 2014 ; Giffi et al., 2014 ; Gupta et al., 2012 ; Hapuwatte et al., 2016 ; Huang et al., 2013 ; Sossou et al., 2018 ; Vaneker, 2017 ; Yang et Zhao, 2015).

L'évaluation de la performance durable ou des indicateurs de performance (SPI) est nécessaire pour comprendre comment la performance durable a été envisagée par la littérature. Il apparaît que la prise en compte des trois dimensions n'est pas équilibrée. Elle aboutit à une liste incomplète, incohérente et insuffisante d'indicateurs de performance durable (SPI) pour chaque dimension (Ahmad et al., 2018; Cohen et al., 2014; Rachuri et al., 2011; Ahmad et al., 2018). Il est donc nécessaire d'avoir une compréhension globale et une considération équilibrée de tous les SPI tout au long du cycle de vie du produit alors que les SPI actuellement identifiés sont davantage axés sur l'évaluation de la performance environnementale (Ahmad et al., 2018 ; Buchert et al., 2014 ; Rossi et al., 2016 ; Yuan et al., 2012 ; Jain, 2005 ; Ahmad et al., 2018 ; Eastwood et Haapala, 2015 ; Haapala et al., 2013 ; Joung et al., 2013 ; Shao et al., 2017 ; Yuan et al., 2012). Une fois que la liste complète des indicateurs est établie sur la base des trois dimensions de la performance durable, il est nécessaire d'élaborer des modèles complets d'aide à la décision pour d'évaluer la performance durable sous toutes ses dimensions (Badurdeen et Jawahir, 2017).

Une évaluation pertinente de la performance durable passe par le développement de nouvelles méthodologies de décision multicritères qui peuvent décrire, analyser, évaluer et optimiser formellement les mesures de performance durable pour les processus et les systèmes de fabrication (Shao et al., 2017). Les concepteurs qui souhaitent promouvoir la fabrication durable doivent pondérer des facteurs tels que le temps, la qualité, les ressources et les coûts, ainsi que les performances environnementales. Des conflits entre les facteurs environnementaux, économiques et sociaux sont très probables et nécessitent l'application et le développement de la prise de décision multicritères (MCDM) (Haapala et al., 2013).

Ainsi, les motivations fondamentales de cette étude sont basées sur le désir de:

- Clarifier la compréhension et les définitions de la performance durable en fabrication;
- Identifier ce qui est nécessaire pour évaluer la performance durable de la fabrication d'un produit: du point de vue du processus de fabrication;
- Identifier, analyser la performance durable des procédés de fabrication additive, évaluer les indicateurs de performance durable existants;

- Identifier, choisir et proposer une approche générale de la méthodologie de prise de décision multicritères pour l'évaluation de la performance durable.

Différents défis restent à relever dans le cadre de cette étude:

- Subjectivité de la définition ou de la compréhension du terme de performance durable lui-même par les chercheurs et les industries. Cette subjectivité peut conduire à des malentendus entre les chercheurs et les industries sur des questions similaires liées à la performance durable;
- Liste incomplète et incohérente des SPI. Il existe toujours une incohérence, un manque de considération équilibrée, un manque de mise à jour, une description incomplète des indicateurs basées sur chaque dimension de la performance durable;
- Évaluation basée sur une analyse comparative de la performance durable des procédés de fabrication additive par rapport aux méthodes de fabrication conventionnelles;
- Absence d'un cadre décisionnel multicritères complet et correctement validé pour évaluer la performance de performance durable d'un produit.

Les questions de recherche suivantes ont été soulevées et abordées au cours de l'étude:

- Quel type de subjectivité existe-t-il dans la compréhension de la performance durable?
- Quels sont les indicateurs de performance durable les plus pertinents dans la conception et la fabrication de produits d'ingénierie?
- Lequel est le plus efficace? La production de produits durables ou la performance durable de la fabrication?
- Quels sont les paramètres pertinents nécessaires pour évaluer la performance durable de la fabrication additive?
- Comment peut-on développer des mesures et/ou des outils pour améliorer la performance durable globale de la fabrication?
- Comment évaluer la performance durable de la fabrication additive par rapport à la fabrication conventionnelle? La performance durable dépend-elle du produit ou de la pièce?

- Que peut-on faire pour aider les décideurs à concevoir des produits ou des processus de manière à assurer la performance durable tout au long du cycle de vie du produit ?
- Parmi les méthodes de prise de décision existantes, lesquelles sont les plus efficaces/préférables pour la prise de décision multicritères? Pourquoi?

Ainsi, l'objectif général de cette étude est de développer une méthodologie complète de prise de décision multicritères pour la performance durable dans la conception et la fabrication de produits d'ingénierie en considérant la technologie de fabrication additive comme une méthode de fabrication concurrentiel. Trois principaux objectifs spécifiques sont envisagés:

1. Elaboration d'une liste complète d'indicateurs de performance de performance durable qui peuvent être comparés aux normes par le biais d'une étude documentaire et d'une comparaison avec les ensembles d'indicateurs et les lignes directrices existants.
2. Analyse de la performance durable de la fabrication additive par une comparaison avec les procédés de fabrication conventionnels sur la base de la littérature existante en se concentrant sur les schémas de sélection des critères, les exigences de modification de la conception et les approches de sélection des paramètres.
3. Développement d'une méthodologie de prise de décision multicritères pour l'évaluation de la performance durable en utilisant le processus de hiérarchie analytique. Cette méthode est considérée comme une solution générale qui peut être utilisée comme référence pour la conception et la fabrication de produits d'ingénierie. Un cas de fabrication d'un support de visière est pris comme une application pour la validation et l'évaluation de la pertinence de la méthodologie proposée.

La première partie de cette étude est axée sur l'identification, la catégorisation et la compilation correcte d'une liste complète d'indicateurs de performance de performance durable basés sur des études du cycle de vie des produits. La deuxième partie de l'étude est axée sur l'analyse de la performance durable de la fabrication additive, via une analyse documentaire qui a permis d'identifier les avantages, les inconvénients et la pertinence de la fabrication additive et des méthodes de fabrication conventionnelles. La troisième et dernière partie de l'étude contribue au développement d'une méthodologie complète de prise de décision multicritères en utilisant le processus de hiérarchie analytique (AHP) qui prend en compte les activités de conception de performance durable et l'optimisation des processus de production où un cas de support d'écran est pris comme demande de validation de la pertinence et de l'efficacité de la méthodologie proposée.

## Chapitre 2: Revue de littérature

*Le lecteur retrouvera les équations, figures et tableaux dans le corps de la thèse.*

La revue de littérature porte sur la performance durable, la fabrication durable, les tendances actuelles en matière de conception et de fabrication et sur les méthodes de prise de décision axées sur un processus de prise de décision multicritères de la hiérarchie analytique.

### *Notion de performance durable et indicateurs de performance durable*

Dans un premier temps, une définition plus complète de la performance durable est proposée par (Haapala et al., 2013 ; Yuan et al., 2012), car elle analyse à la fois la performance environnementale et les considérations de système socio-économique des processus et systèmes de fabrication. La performance durable ne peut pas être assimilée à la performance environnementale ou à l'écoconception. Selon la littérature, il y a un déséquilibre dans la prise en compte des trois dimensions. Par exemple, les dimensions environnementales ont été au centre des recherches actuelles et les dimensions sociales ont été considérées comme les moins importantes. La plupart des études récentes recommandent d'équilibrer les priorités économiques et financières par rapport aux priorités environnementales et sociales (Ahmad et al., 2018 ; Eastwood et Haapala, 2015 ; Shao et al., 2017 ; Zhang et al., 2013).

Ainsi, La conception et la fabrication durables consistent à créer des produits manufacturés qui utilisent des procédés qui minimisent les impacts négatifs sur l'environnement, conservent l'énergie et les ressources naturelles, sont sûrs pour les employés, les communautés et les consommateurs et sont économiquement sains (Ahmad et al., 2018 ; Moktadir et al., 2018 ; Shao et al., 2017 ; Peralta Álvarez et al., 2017). Selon (Joung et al., 2013), les dimensions de la performance durable sont classées en cinq catégories: gestion de l'environnement, croissance économique, bien-être social, progrès technologique et gestion des performances. Dans ce cadre, les principales dimensions sont rapportées comme capital environnemental, capital économique et capital humain. Il est montré que pour produire les produits et services demandés par la société, les industries consomment les ressources de la nature, les ressources humaines sous forme de connaissances et rejettent des émissions et des déchets et exposent la société à la pollution.

Les indicateurs de performance durable (SPI) sont utilisés pour quantifier les performances durables. Jusqu'à présent, la prise en compte des indicateurs de performance durable (SPI) est incomplète et subjective. Les travaux n'ont pas développé des SPI simples, complets et de haut niveau qui peuvent être quantifiés et comparés à des normes pour diverses applications (Ahmad et al., 2018 ; Cohen et al., 2014 ; Rachuri et al., 2011). Selon (Badurdeen et Jawahir, 2017), les indicateurs peuvent être utilisés pour développer un modèle complet d'aide à la décision pour

l'évaluation de la performance durable du cycle de vie total qui prend en compte les innovations au niveau des produits, des processus et des systèmes, ce qui permet d'évaluer la performance durable sous tous ses aspects. La plupart des SPI actuellement identifiés sont plus axés sur l'évaluation de la performance environnementale (Ahmad et al., 2018 ; Buchert et al., 2014 ; Rossi et al., 2016 ; Yuan et al., 2012) que sur la prise en compte d'indicateurs complets de performance durable (Jain, 2005). Des travaux supplémentaires sont donc nécessaires pour identifier, quantifier et générer une liste et une description complètes des SPI. Le tableau 2.1 présente des représentants de mesures (indicateurs) selon les documents cités à titre de référence, notamment en ce qui concerne la connaissance de l'indicateur, la stratégie de mesure et les moyens possibles de le déterminer dans le produit. D'après (Peralta Álvarez et al., 2017), il semble que les dimensions de la performance durable doivent être prises en compte de manière équilibrée:

1. Dimension économique : paramètres de contrôle, liquide de refroidissement, coût, conditions de coupe, fluide, gestion de l'information, lois et normes, apprentissage de la machine, enlèvement de matière, ressources en énergie et en eau, intrants, usinage intelligent, surface de qualité, énergie thermique, temps, outil.
2. Dimension environnementale: Empreinte carbone, empreinte écologique, impact environnemental, gaz à effet de serre, empreinte hydrique, impacts, inventaire, matériaux, matières premières, ressources, émission de substances, toxicité, flux de déchets.
3. Dimension sociale : Accident, tâche cognitive, confort / gêne, ergonomie et facteurs humains, machine à rétroaction (tâche d'information), comportement humain, multiréponse, risque, sécurité et santé, sémantique, compétences (travailleur), population particulière, formation, bien-être, lieu de travail, ingénierie Kansei et sentiments psychologiques.

La fabrication durable (SM) est identifiée comme l'un des indicateurs de performance prioritaires par le ministère américain du commerce (Shao et al., 2017) en raison de ses capacités à la fois à améliorer la qualité de vie et à minimiser la charge sur l'environnement par les systèmes de fabrication mécanique (SMM) traditionnels. Afin d'atteindre les objectifs de fabrication durable, (Haapala et al., 2013) recommande de se concentrer sur quatre catégories: processus et équipements de fabrication, systèmes de fabrication, changements de paradigmes du cycle de vie et éducation. Une autre définition plus élaborée de la fabrication durable donnée par (Moktadir et al., 2018) est l'utilisation de matériaux renouvelables, la réduction de l'utilisation de matériaux et d'intrants qui ne sont pas dangereux, la modification du processus de production qui utilise moins de matériaux et d'énergie, l'utilisation de systèmes de transport et de logistique plus efficaces, la conception de produits réutilisables, la refabrication, le recyclage et la biodégradation et la collaboration avec les parties prenantes et les clients pour réduire l'impact environnemental

de l'industrie. Ainsi, pour atteindre les objectifs de fabrication durable, l'accent doit être mis sur quatre catégories: processus et équipements de fabrication, systèmes de fabrication, changements de paradigmes du cycle de vie et éducation. Le ministère américain du commerce définit la fabrication durable comme la création de produits manufacturés utilisant des processus qui minimisent les impacts négatifs sur l'environnement, conservent l'énergie et les ressources naturelles, sont sûrs pour les employés, les communautés et les consommateurs et sont économiquement sains grâce à la récupération de la valeur des produits en fin de vie (Badurdeen et Jawahir, 2017 ; Kulatunga et al., 2015 ; Li et Mathiyazhagan, 2018 ; Pigosso et McAloone, 2015 ; Shao et al., 2017).

#### *Fabrication additive durable*

La fabrication additive (AM) est un procédé de fabrication d'objets 3D par ajout couche après couche (assemblage) de matériaux (Gebisa et Lemu, 2017; Gupta et al., 2012 ; Nathan, 2015 ; Sossou et al., 2018). Aujourd'hui, cette technologie est appliquée à la production de pièces de service (Nathan, 2015). D'après diverses publications, l'AM présente un meilleur avantage que les procédés de fabrication conventionnels (CM) pour aborder la question de la fabrication durable (Gardan et Schneider, 2015 ; Gebisa et Lemu, 2017 ; Huang et al., 2013 ; Jared et al., 2017 ; Nathan, 2015 ; Sossou et al., 2018 ; Tang et al., 2016 ; Thompson et al., 2016).

Outre les avantages mentionnés, les limitations courantes de la fabrication additive comprennent le coût élevé des machines et des matériaux comme investissement initial, le mauvais état de surface (cause d'activités de post-traitement prolongées), un volume de production et une vitesse de construction moindres (raison de la faible productivité), la stabilité dimensionnelle, l'incertitude des propriétés mécaniques de la pièce finale, le coût élevé des équipements et des matériaux de la fabrication additive, l'impact de la poudre sur la santé humaine, etc. Le fait de compléter les activités de post-traitement permet d'améliorer la microstructure, de réduire la porosité et de finir les surfaces, de réduire la rugosité et de respecter la tolérance géométrique. Toutefois, plusieurs stratégies sont également mises en œuvre pour minimiser ces défis. (Bikas et al., 2016 ; Bourell et al., 2017 ; Frazier, 2014 ; Giffi et al., 2014 ; Gupta et al., 2012 ; Hapuwatte et al., 2016 ; Huang et al., 2013 ; Sossou et al., 2018 ; Vaneker, 2017 ; Yang et Zhao, 2015). Actuellement une vaste gamme d'application et de procédés existent.

#### *Méthodes de conception et développement de produits durables*

Lors du développement de produits durables, il est essentiel de prendre en compte l'objectif de la démarche (conception d'un nouveau produit, amélioration d'un produit ou d'un processus) et de s'intéresser à toutes les étapes du cycle de vie du produit (de la pré-fabrication à la post-utilisation). Selon (Buchert et al., 2014), il faut également prendre en compte le domaine

d'application, la performance durable basée sur l'approche TBL, le type de données, et le point de vue de l'utilisateur. Selon (Ahmad et al., 2018), la conception traditionnelle des produits se concentre sur les fonctionnalités, la qualité et le coût des produits pour répondre aux exigences des clients, tandis que la conception durable des produits (SPD) considère systématiquement l'ensemble du cycle de vie des produits en termes de fonctionnalité, d'environnement et de performance économique.

Mentionnée comme roue de la performance durable des produits, la figure 2.7 représente les six éléments majeurs de la performance durable des produits et plusieurs sous-éléments. Outre le développement d'approches de quantification, il est nécessaire d'étudier pleinement leurs effets sur la performance durable des produits.

Ainsi, il est nécessaire de comprendre les principes de l'ingénierie simultanée, d'identifier les produits possibles pour la fabrication additive et d'évaluer les tendances existantes en matière de conception et de fabrication. L'ingénierie simultanée (EC) est définie comme "une approche systématique de la conception intégrée et simultanée de produits et des processus associés, y compris la fabrication et le support. Elle vise à inciter les concepteurs/développeurs de produits à prendre en compte tous les éléments du cycle de vie des produits dès les premières étapes de leur développement (Tang et al., 2000 ; Xu et al., 2007).

### *Evolution de la conception et de la fabrication*

Les tendances futures en matière de conception et de fabrication doivent aller au-delà des exigences de réussite de la conception, du développement et de la fabrication des produits, comme le signale (Johansson, 2002). Ces exigences comprennent l'intégration des fournisseurs, la performance des processus, la direction des projets, le système de gestion, l'implication des clients, l'efficacité du développement du concept de produit (adéquation avec les besoins du marché et avec les compétences de l'entreprise), le marché et les performances financières, mais n'ont pas montré que l'environnement était un facteur clé.

Afin d'obtenir une meilleure performance durable des processus de fabrication, il est également nécessaire de prendre en compte de nouvelles exigences et de tenir compte des limites des procédés, selon les inventaires américains du cycle de vie des procédés unitaires (UPLCI) et le CO2PE européen (Haapala et al., 2013). Selon (Gupta et al., 2012 ; Haapala et al., 2013 ; Moldavska et Welo, 2017), le développement de produits durables doit tenir compte de la consommation des ressources, de la pollution, de la sécurité et du risque pour l'homme et l'écosystème, de la performance durable. En ce qui concerne la responsabilité sociale et les préoccupations écologiques, les Nations Unies (ONU) définissent des objectifs de développement durable pour minimiser les impacts environnementaux, économiques et sûrs pour les employés



et les communautés (Ahmad et al., 2018 ; Ceschin et Gaziulusoy, 2016 ; Eastwood et Haapala, 2015 ; Madan Shankar et al., 2017 ; Zhang et al., 2013).

En conclusion, la tendance actuelle est à l'intégration des opérations produit-service pour maximiser la performance durable environnementale, économique et sociale de la fabrication avancée.

### *Méthodes de prise de décision et performance durable*

Les ouvrages publiés à ce jour ont tenté d'aborder les questions de performance durable des procédés conventionnels dans différents contextes et pour diverses applications, mais aucun n'a pu proposer de cadres et de stratégies complets pour y répondre pleinement. L'un des principaux problèmes est le manque de prise en compte exhaustive des indicateurs de performance (SPI) tout au long du cycle de vie du produit (CPL) et l'absence de prise en compte équilibrée des trois dimensions de la performance durable (Peralta Álvarez et al., 2017 ; Reich-Weiser et al., 2008).

Pour atteindre les objectifs de fabrication durable, il est nécessaire de prendre en compte la prise de décision en ingénierie pour définir l'objectif, générer une solution possible et prévoir la préférence, compte tenu de l'ensemble des contraintes associées à la performance durable.

Une bonne décision donne toutes les alternatives disponibles dont on dispose, toutes les informations dont on dispose et les préférences une fois évaluées. C'est une décision qui est systématiquement correcte, compte tenu d'une situation de décision bien encadrée par un décideur engagé. La qualité d'une décision repose sur le fait de l'avoir correctement formulée, c'est-à-dire de répondre à la bonne question, de comprendre les problèmes (connaissances), ce qui peut être fait (options) et voulu (résultats souhaités).

Selon (Bereketli et Erol Genevois, 2013; Brones et Monteiro de Carvalho, 2015; Dufrene et al., 2013), plusieurs études ont été réalisées pour établir des méthodologies et des cadres de performance durable dans la conception environnementale des produits mais n'ont pas fourni de cadre précis pour l'identification des stratégies d'amélioration pertinentes liées aux caractéristiques des pièces. En outre, elles ont proposé une hiérarchie visant à pondérer les exigences des clients en tenant compte du coût, de la qualité et des préoccupations environnementales, ainsi que de nombreuses alternatives qui n'étaient pas complètes pour aborder la performance durable. L'une des études les plus récentes (Ahmad et al., 2018), témoigne que la recherche en ingénierie n'a pas réussi à fournir les outils appropriés pour aider à la prise de décision sur le système de fabrication qui se concentre maintenant sur l'équilibre des trois dimensions de la performance durable. D'autres études sont nécessaires pour développer



de nouvelles méthodologies permettant de décrire, d'analyser, d'évaluer et d'optimiser les mesures de performance durable pour les processus et/ou les systèmes de fabrication.

(Shao et al., 2017) résume plusieurs études de cas qui ont pris en compte la performance durable dans des processus de conception. Cependant, aucune de ces approches n'a utilisé une description modulaire réutilisable des connaissances sur les processus et les analyses de performance durable pour l'analyse et la prise de décision. Par ailleurs, une étude très complète sur les avantages, les inconvénients et les applications des onze méthodes d'analyse décisionnelle multicritères (MCDA) les plus connues est présentée par (Velasquez et Hester, 2013): Théorie de l'utilité multi-attributs (MAUT); Processus de hiérarchie analytique (AHP); Théorie des ensembles flous (FST); Raisonnement basé sur des cas (CBR); Analyse des équipements de données (DEA); Technique de notation multi-attributs simple (SMART); Programmation des objectifs (GOP); ELimination Et Choix Traduisant la Réalité (ELECTRE); Organisation de classement des préférences; METHODE d'enrichissement des évaluations (PROMEETHEE); Pondération additive simple (SAW); Technique d'ordre de préférence par similarité avec la solution idéale (TOPSIS).

En conclusion, il est très important de comprendre les avantages, les inconvénients et les applications de ces méthodes MCDA largement connues afin d'ajuster les préférences des chercheurs en matière de méthodologies.

### *Processus de hiérarchisation analytique AHP*

L'AHP (Analytic Hierarchy Process) est l'une des méthodes de prise de décision multicritères les plus puissantes développées par le professeur Thomas L. Saaty (Saaty et Vargas, 2012). Il s'agit d'une théorie générale de mesure qui est utilisée pour piloter les échelles de rapports à partir de comparaisons par paires, tant discrètes que continues, dans des structures hiérarchiques à plusieurs niveaux (Haapala et al., 2013 ; Saaty et Vargas, 2012). La méthode utilise des comparaisons par paires pour simplifier l'évaluation des préférences parmi les critères de décision et fournit des mesures de la cohérence du jugement et détermine les priorités parmi les critères et les alternatives. La méthode est également utilisée pour les décisions relatives à la planification stratégique, à l'allocation des ressources, aux politiques commerciales et publiques, à la sélection des programmes.

Selon (Mu et Pereyra-Rojas, 2017), la méthode AHP est utile pour évaluer les critères qualitatifs et quantitatifs sur une même échelle de préférence. Elle facilite la modélisation hiérarchique ou la structuration des problèmes, elle adopte des jugements verbaux et permet de vérifier la cohérence. En outre, elle est intégrée dans le logiciel convivial (Expert Choice, Super choice, Decision Lens), ce qui montre qu'elle trouve diverses options logicielles et qu'elle peut être utilisée

conjointement avec d'autres méthodes. La mise en œuvre de l'AHP suit différentes étapes comme proposé par (Ishizaka et Labib, 2009; Saaty et Vargas, 2012; WANT et BAD, 1990). Les problèmes sont d'abord décomposés en une hiérarchie de critères et d'alternatives, puis le problème est analysé en traitant les critères (critères 1, 2, 3 ...n) et les alternatives possibles (alternatives: 1, 2, 3 ...n). Ainsi, il est important d'énoncer l'objectif, de définir ou d'identifier les critères et enfin de choisir les alternatives.

Pour l'évaluation, l'AHP a besoin d'échelles de comparaison fondamentales (échelle de Saaty), comme le montre le tableau 2.6, en raison de ses comparaisons par paires. Pour déterminer les priorités, les comparaisons verbales doivent être converties en comparaisons numériques en utilisant les échelles de Saaty entre 1 et 9, utilisées dans la plupart des applications.

Des comparaisons redondantes sont faites pour améliorer la validité des réponses, car les décideurs peuvent être incertains ou porter de mauvais jugements pour la comparaison de certains éléments.

#### *Méthodologies nécessaires à la performance durable de la fabrication*

Dans le cadre de la recherche actuelle sur la fabrication durable, des efforts importants sont consacrés à la mise au point de mesures et d'outils pour l'analyse des performances environnementales des processus de fabrication. Mais peu de travaux ont été réalisés au niveau de la réflexion systémique pour l'élaboration d'une approche visant à améliorer la performance durable globale de la fabrication (Yuan et al., 2012) qui tient également compte des dimensions économiques et sociales. Il est nécessaire de mentionner certaines méthodologies qui contribuent à la performance durable des processus de fabrication. Une étude de (Jin et al., 2017), mentionne les apports importants suivants:

- Méthodes de décision multi-objectifs pour optimiser la consommation d'énergie et la qualité des produits comme objectifs;
- Utilisation de l'analyse des données par éléments finis dans les méthodes de fabrication conventionnelles pour analyser la relation entre les variables de processus, la force de coupe et la consommation d'énergie afin de minimiser la consommation d'énergie en réduisant la force de coupe;
- Algorithme AMOPSO (Adaptive Multi-Objective Particle Swarm Optimization) utilisé pour proposer un modèle d'optimisation des paramètres multi-objectifs afin de maximiser l'efficacité énergétique et de minimiser les coûts de production;

- Algorithme FSGA (Fitness Sharing Genetic Algorithm) utilisé pour réduire la consommation d'énergie et améliorer l'efficacité thermique des procédés de soudage à l'arc;
- Planification non linéaire des processus (NLPP), un modèle mathématique intégrant la planification et l'ordonnancement des processus, utilisée pour minimiser la consommation d'énergie de l'usinage;
- Fabrication cellulaire dynamique - système de service produit (DCM-PSS) utilisée pour intégrer la fabrication et le service, ce qui améliorera la performance durable des performances économiques et sociales (une boucle fermée de la conception du produit et du processus. Traitement des matières premières, fabrication à la commande et fabrication de produits);
- Approche combinée du principe de la pensée systémique de la fabrication durable sous la forme de la dynamique des systèmes pour développer un modèle conceptuel, envisagée par (Zhang et al., 2013) pour comprendre l'interaction complexe des facteurs au sein du système défini;
- Outil MCDM appelé DEMATEL utilisé pour évaluer l'influence des pratiques de fabrication durable parmi 22 pratiques courantes de fabrication durable classées selon les trois piliers de la performance durable (Madan Shankar et al., 2017). L'analyse a révélé que la "promotion des 6R" est devenue la plus influente et que « l'amélioration des performances des processus » est devenue la moins influente;
- Cadre de conception pour une fabrication durable (DfSM) élaboré (Haapala et al., 2013) qui regroupe les questions internationales, les questions contemporaines et les produits innovants, les systèmes de fabrication reconfigurables, les stratégies de fabrication, les mesures de performance et la gestion organisationnelle flexible en un seul indice en utilisant une approche de somme pondérée;
- Analyse des flux de matières et analyse des flux d'énergie pour quantifier et suivre les flux de matières/énergie dans le secteur manufacturier (Yuan et al., 2012);
- Méthodologie d'évaluation durable (qui utilise la modélisation des processus unitaires et les techniques d'inventaire du cycle de vie), développée par (Eastwood et Haapala, 2015) pour améliorer la précision des approches existantes dans l'identification des impacts de performance durable d'un produit et aussi pour aider les décideurs du secteur manufacturier;

- Formalisme analytique des processus durables (SPAF) développé pour effectuer une analyse de performance durable qui est introduite par (Shao et al., 2017) comme méthodologie systémique de guide de décision, pour interroger les données, effectuer une analyse de simulation et optimiser les décisions pour des mesures durables;
- Valeur non capturée, proposée comme nouvelle perspective pour l'innovation de modèles d'entreprise durables: valeur en surplus, valeur absente, valeur manquée et valeur détruite.

### *Résumé et implications*

Selon l'analyse documentaire présentée, il apparaît que de nouvelles méthodes de conception permettent une plus grande intégration de l'écoconception dans la conception et le développement des produits. Cette intégration vise essentiellement à minimiser les impacts environnementaux négatifs tout au long du cycle de vie du produit. Mais cette considération omet les dimensions économiques et sociales de la performance durable. Ainsi, le défi actuel identifié consiste à équilibrer les dimensions de la performance durable.

Les autres résultats concernent la quantification des indicateurs de performance de performance durable pour l'ensemble du cycle de vie des produits. La plupart des études utilisent des facteurs de décision couramment utilisés tels que la productivité, le coût, la consommation d'énergie, etc.

A la suite de cette étude, il convient de se poser la question de la subjectivité de la performance durable. Dans le processus de conception et de fabrication, des conflits entre les dimensions de la performance durable sont probables lors de leurs considérations simultanées, ce qui nécessitent l'application et le développement d'une prise de décision multicritères. Dans la conception et le développement de produits durables, l'établissement de méthodologies et la proposition de nouveaux modèles, indicateurs et stratégies sont nécessaires pour une prise en compte équilibrée et simultanée des indicateurs de performance afin d'éviter les problèmes de subjectivité.

Ainsi, lors de l'examen des trois dimensions de la performance durable, il est recommandé d'accorder une grande importance à l'équilibre et à l'exhaustivité de chaque dimension. Un examen plus approfondi est nécessaire, pour proposer une liste complète d'indicateurs de performance durable. Une fois la liste d'indicateurs identifiée, il est nécessaire d'utiliser une méthodologie originale pour envisager des compromis entre les différents indicateurs de performance. Elle permet de décrire, analyser, évaluer et optimiser les mesures de performance durable pour les processus et/ou systèmes de fabrication. Le développement de mesures et d'outils est plus répandu pour les performances environnementales que pour toutes les dimensions, y compris économiques et sociales. Ainsi, de nouveaux paramètres ou indicateurs de

performance durable devraient être développés pour améliorer la performance globale de la fabrication en matière de performance durable.

Les possibilités de conception pour la fabrication additive devraient également être exploitées grâce à une bonne compréhension des exigences relatives aux procédés de fabrication conventionnels et additives. En outre, les tendances en matière de conception et de fabrication montrent une meilleure intégration des fournisseurs, des performances des processus, du leadership, de la gestion des systèmes, de l'implication des clients, etc, dans le cadre de la fabrication additive.

En ce qui concerne les méthodes de prise de décision, la littérature observe que le processus de hiérarchie analytique (AHP) est la méthodologie de prise de décision la plus pertinente. Elle utilise la comparaison par paires, la notation des préférences simples et la vérification de la cohérence, et établit des priorités parmi les critères de décision. Elle permet d'examiner simultanément des indicateurs et de faire des compromis numériques pour arriver à une synthèse ou à une conclusion.

Il est donc nécessaire d'étudier et d'analyser les possibilités de minimiser ou d'éviter la compréhension subjective de la performance durable en fournissant une liste complète des performances en matière de performance durable. Ainsi, l'objectif principal de cette étude est l'analyse de la performance de performance durable du processus de fabrication des additifs, le développement d'une liste complète d'indicateurs de performance durable et enfin la proposition d'une application d'une méthodologie de prise de décision multicritères avec l'aide de l'AHP dans la conception et la fabrication de produits techniques.

### **Chapître 3: Méthodologie de recherche**

La méthodologie de recherche repose sur une première étape, qui est une évaluation de la performance durable des procédés de fabrication additive. La deuxième étape consiste à élaborer une liste complète d'indicateurs de performance de performance durable (SPI). Pour y parvenir, une étude et une analyse bibliographique plus larges ont été réalisées afin d'identifier les lacunes existantes associées à la performance durable elle-même, à la fabrication durable, ainsi qu'aux tendances en matière de conception et de fabrication. La troisième et dernière étape consiste à développer une méthodologie complète de prise de décision multicritères en utilisant le processus de hiérarchie analytique (AHP) pour évaluer la performance durable d'un produit d'ingénierie, lorsqu'il est fabriqué par des procédés de fabrication alternatifs tels que la fabrication conventionnelle ou additive (chapitre 6). Ainsi, le cadre de recherche de la thèse est basé sur la prise en compte des résultats de l'analyse documentaire et des tendances actuelles de la conception et de la fabrication des produits ainsi que sur la nécessité de la performance durable.

## Chapître 4: Analyse de la performance durable de la fabrication additive

La question d'évaluer la performance durable d'un nouveau procédé est critique. Généralement le développement d'un nouveau procédé répond à des attentes différentes et la performance durable n'est pas abordée *a priori*. Il convient alors d'en évaluer l'impact. Intrinsèquement, la fabrication additive semble présenter des qualités durables (DebRoy et al, 2018 ; Džugan et Novy, 2017 ; EPAM, 2015 ; Hasan et Rennie, 2008 ; Vishnu Prashant Reddy et al., 2018 ; Zwier et Wits, 2016). Afin d'analyser la performance durable de la fabrication additive, les informations primaires doivent être classées en fonction des exigences du cycle de vie du produit. Le tableau 4.1 présente la liste des critères d'évaluation et leur adaptation aux procédés de fabrication additifs ou conventionnels.

La fabrication additive présente l'avantage prometteur d'aborder les questions de fabrication durable par rapport à de nombreux procédés conventionnels. La meilleure performance durable est due à la réduction du poids et des coûts, et à la minimisation de l'impact environnemental et social négatif, notamment en cas de complexité et de personnalisation élevées des pièces. Il permet également de concevoir et de produire des pièces multi-matériaux, multifonctionnelles, monolithiques et personnalisées, ce qui est indirectement lié à notre consommation de ressources et à l'impact environnemental, économique et sociétal. Selon (Frazier, 2014), la fabrication additive est censée minimiser l'impact négatif sur l'environnement grâce à une utilisation efficace des ressources.

Le tableau 4.2 fait état de plusieurs possibilités offertes par les procédés de fabrication additive par rapport aux procédés de fabrication conventionnels pour une meilleure performance durable sur la base des trois dimensions. Cependant, les limitations associées telles qu'un mauvais état de surface (cause d'une prolongation des activités de post-traitement), un volume de production et une vitesse de construction moindres (raison de la faible productivité), la stabilité dimensionnelle, l'incertitude des propriétés mécaniques de la pièce finale, le coût élevé des équipements et des matériaux, l'impact de la poudre sur la santé humaine, etc. sont également identifiées. Les activités de post-traitement sont utilisées pour améliorer la microstructure, réduire la porosité et pour finir les surfaces, réduire la rugosité et respecter la tolérance géométrique. Mais plusieurs stratégies sont également mises en œuvre pour minimiser ces défis. (Bikas et al., 2016 ; Bourell et al., 2017 ; Frazier, 2014 ; Giffi et al., 2014 ; Gupta et al., 2012 ; Hapuwatte et al., 2016 ; Huang et al., 2013 ; Sossou et al., 2018 ; Vaneker, 2017 ; Yang et Zhao, 2015).

En conclusion, on peut constater que la performance durable des procédés de fabrication additive par rapport aux procédés de fabrication conventionnels est basée sur la réduction des impacts négatifs et de renforcement des impacts positifs de performance durable. En outre, grâce à la mise en œuvre de différentes stratégies visant à réduire au minimum les limitations ou les

difficultés constatées pour six des facteurs de sélection identifiés, il est possible d'obtenir une meilleure performance durable pour la fabrication additive. Sur la base de ces possibilités, la pertinence de la fabrication additive pour une meilleure performance durable est évaluée selon les facteurs suivants pour un processus de fabrication : coût d'assemblage minimisé, stratégie de construction à la commande, formation de caractéristiques complexes, flexibilité de la conception, utilisation efficace des matériaux, fabrication d'objets intégrés, émission minimisée, risque sanitaire minimisé (pas de poudre pour le support), fabrication juste à temps, délai de livraison minimisé, contraintes minimisées (pas de contraintes), consommation de matériaux minimisée, capacité de fabrication de structures monolithiques, risque professionnel minimisé, réalisation d'une conception optimisée, meilleure réactivité, exigence de transport minimisée (coût) et forte probabilité d'élimination des déchets. Par conséquent, la fabrication avec un minimum de contraintes pour une meilleure performance durable peut facilement être réalisée en comprenant les critères de sélection et les exigences d'adaptation de la conception pour exploiter pleinement les possibilités de la fabrication additive.



## Chapitre 5: Indicateurs de performance durable

*Le lecteur retrouvera les équations, figures et tableaux dans le corps de la thèse.*

L'identification, la catégorisation et la description d'une liste exhaustive d'indicateurs de performance (SPI) et de stratégies de mesure peut servir de référence pour évaluer les alternatives, les choix politiques, quantifier et étalonner les performances durables des processus de conception et de fabrication des produits. Pour cela, une approche descendante de l'identification de la performance durable dans les dimensions environnementales, économiques et sociales est utilisée. La figure 5.1 propose une liste d'indicateur de performance spécifique.

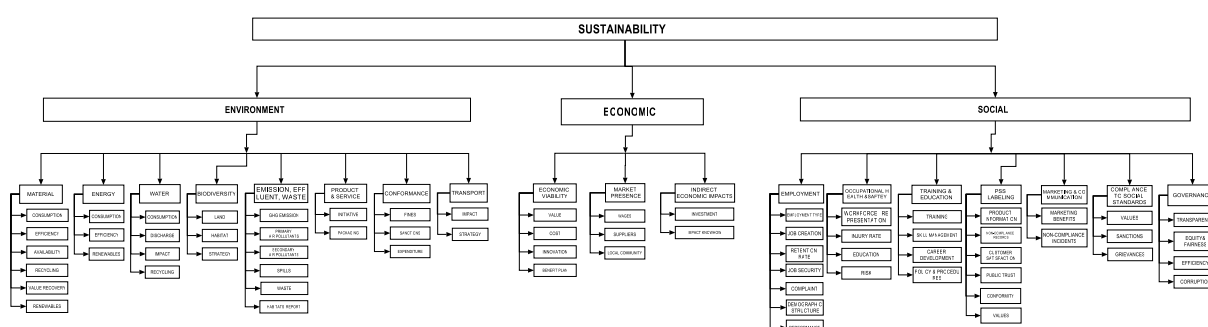


Figure 5.1 Indicateurs de performance de performance durable proposés

La catégorisation et la proposition de SPI sont présentées en fonction de trois dimensions, à savoir l'environnement, l'économie et la société. En outre, pour chaque dimension, les catégories de deuxième et troisième niveau (catégories et sous-catégories) de ces indicateurs sont indiquées. La catégorie de deuxième niveau comprend 18 indicateurs (8 pour l'environnement, 3 pour l'économie et 7 pour le social) et la sous-catégorie de troisième niveau 68 indicateurs dont 29 pour l'environnement, 9 pour l'économie et 30 pour le social. Une fois ces catégories élaborées, la stratégie d'interprétation et de quantification est présentée, le cas échéant, dans les tableaux 5.1, 5.3 et 5.5.

Les tableaux 5.2, 5.4 et 5.6 indiquent le nombre de références citées et le nombre d'indicateurs (SPI) mentionnés par chaque référence, comme le montre la dernière colonne de chaque tableau indiquant la fréquence à laquelle chaque SPI proposé est mentionné dans chacune des références citées. Ainsi, il est clairement observé que 48 références sont citées pour les indicateurs de performance environnementale, 23 pour les indicateurs économiques et 34 pour les indicateurs de performance sociale. En outre, le nombre d'indicateurs proposés à partir d'une seule référence est beaucoup plus important pour les indicateurs de performance environnementale que pour les indicateurs de performance économique et sociale. Par exemple, l'observation des tableaux montre que plus de 5 SPI sont mentionnés dans 15 références en environnement, 1 référence en économie et 7 références en dimension sociale. Cela indique donc que l'environnement a fait l'objet de plusieurs études dans le passé.

La validation de l'exhaustivité de la liste d'indicateurs de performance proposée est faite en la comparant avec dix des ensembles d'indicateurs et des lignes directrices les plus formalisés dans la littérature, qui essaient de traiter toutes les dimensions de la performance durable dans différents contextes et applications. Les dix ensembles d'indicateurs représentatifs et les lignes directrices sont étudiés afin de valider l'exhaustivité des SPI proposés. La GRI 2000 est une ligne directrice élaborée sur la base de l'objectif et des principaux défis de la compréhension du développement durable. Elle tient compte de l'urgence et de l'ampleur des risques et des menaces pour assurer la performance durable et pour accroître les possibilités de transparence sur les impacts économiques, environnementaux et sociaux. La norme ISO 14031 2013 donne des orientations sur la conception et l'utilisation de l'évaluation des performances environnementales (EPE) au sein d'une organisation, quels que soient son type, sa taille, son emplacement et sa complexité. L'ESI 2005 est un indice de performance durable publié par le Yale Center for Environmental Law and Policy, basé sur un atelier d'experts en 2004. Il est élaboré sur la base de l'évaluation des données disponibles, d'une analyse rigoureuse et de la consultation de décideurs politiques, de scientifiques et d'experts en indicateurs, et associe également la performance durable environnementale et les défis du développement et de l'industrialisation ainsi que les facteurs de sous-développement et les défis environnementaux induits par la pauvreté. L'AEE 2005 a produit un ensemble d'indicateurs de base sélectionnés sur la base de critères largement utilisés en Europe et dans l'OCDE. Une attention particulière a été accordée aux priorités politiques, aux objectifs et aux cibles. L'UN-ISD2007 contient des ensembles d'indicateurs de développement durable basés sur les fonctions des indicateurs pour prendre de meilleures décisions et des actions plus efficaces en simplifiant, clarifiant et mettant des informations agrégées à la disposition des décideurs politiques. L'OCED EI 2003 est proposé sur la base de la pertinence des indicateurs pour les rapports environnementaux, la mesure de la performance environnementale et le compte rendu des progrès réalisés en matière de développement durable. L'EPrI examine le contexte de l'utilisation d'indicateurs largement utilisés dans l'élaboration des politiques économiques et sociales et la compréhension des pressions exercées sur l'environnement par les activités humaines. Il permet de mieux comprendre l'intérêt d'avoir une bonne connaissance des problèmes environnementaux actuels et de créer une base pour les politiques environnementales futures. Le DJSI a été créé pour suivre et contrôler les performances des organisations qui s'efforcent d'accroître la valeur des parties prenantes à long terme pendant la transition de la gestion de la qualité des produits à la gestion des services. L'EPfI considère la performance durable environnementale comme une priorité politique essentielle et un programme public dans le monde entier. Une attention particulière est accordée au changement climatique, à la qualité et à la disponibilité de l'eau, à la pollution de l'air, à la déforestation et aux changements d'utilisation des sols, à la biodiversité et à la performance durable de l'agriculture et de la pêche. L'ISP de Ford est un outil de gestion de la performance durable introduit par Ford, sur la base de la prise en compte des aspects environnementaux, économiques et sociétaux.

Le tableau 5.7 présente les résultats de la validation de chacun des 68 SPI par rapport aux ensembles d'indicateurs et aux lignes directrices sélectionnés. Il s'avère que, parmi les 68 indicateurs, 43 des sont mentionnés dans 2 à 9 de ces ensembles d'indicateurs et lignes directrices avec le symbole "×". Mais les 15 autres indicateurs ne sont mentionnés qu'une seule fois et 5 ne sont jamais mentionnés dans chacun de ces ensembles d'indicateurs et lignes directrices. Les 5 indicateurs qui ne sont jamais mentionnés sont tous des indicateurs sociaux et parmi ceux qui ne sont mentionnés qu'une seule fois, 11 sont des indicateurs sociaux et seulement 4 sont des indicateurs économiques, ce qui est pris comme une indication du manque de considération égale la dimension sociale de la performance durable par rapport aux dimensions économique et environnementale. Les 5 indicateurs sociaux sont la conformité, l'équité et la justice, la confiance du public, les sanctions sociales et la transparence et les 4 indicateurs économiques mentionnés une seule fois sont axés sur l'investissement, l'innovation, l'emploi de la communauté locale et la localisation des activités au profit des fournisseurs. En outre, comme décrit dans le contexte de cette étude, ce résultat prouve que les ensembles d'indicateurs et les lignes directrices les plus connus sont axés sur les aspects environnementaux et économiques et que les aspects sociaux de la performance durable sont peu ou pas pris en compte.

Ainsi, une liste complète d'indicateurs de performance de performance durable est proposée et interprétée, et validée pour son exhaustivité en considérant davantage d'indicateurs de performance sociale pour une considération équilibrée de toutes les dimensions pour l'évaluation de la performance durable.

## Chapitre 6: Performance durable des processus de fabrication

*Le lecteur retrouvera les équations, figures et tableaux dans le corps de la thèse.*

A la suite de l'expression d'un ensemble de 68 SPI dans le chapitre précédent, il peut être envisagé de simplifier l'évaluation, en adaptant la liste des indicateurs pertinents pour les processus de fabrication et la performance durable étudiés. Les décideurs ont tendance à sélectionner les SPI qui ont une meilleure importance/impact. Dans ce cas précis, certains indicateurs qui sont indirectement exprimés en fonction d'un autre indicateur de la même catégorie ne sont pas pris en considération.

Un cas de fabrication de supports de visière est pris en compte dans l'application. Cette analyse aide les décideurs à déterminer comment un processus de prise de décision utilisant la méthodologie AHP est utilisé pour choisir les processus permettant d'obtenir de meilleures performances durables. Une méthode de prise de décision multicritère de la méthodologie AHP est utilisée. L'analyse est effectuée pour trois alternatives de procédés de fabrication. Il s'agit du moulage par injection, de l'impression 3D et de la découpe laser. À la fin, la performance durable de chaque processus est rapportée pour chaque dimension, à partir d'un vote préférentiel de Borda.

Le processus de hiérarchie analytique (AHP) est sélectionné pour le fait qu'il est largement accepté et appliqué, qu'il peut évaluer des critères qualitatifs et quantitatifs sur la même échelle de préférence, qu'il facilite la modélisation hiérarchique ou la structuration des problèmes, qu'il adopte des jugements verbaux et qu'il permet de vérifier la cohérence. La première étape du processus consiste à structurer ou à modéliser le problème lorsque cette étape nécessite la construction d'un arbre d'indicateurs après avoir identifié les indicateurs ou les SPI les plus importants et les plus influents de la liste entière. Une fois les SPI importants sélectionnés, des jugements sont portés pour établir la matrice de comparaison par paires. La comparaison par paires consiste à comparer l'importance relative de deux éléments (dans le cadre des critères, sous-critères ou sous-sous-critères) en fonction de la sélection et des jugements effectués sur la base de l'expérience des décideurs qui est basée sur la règle de Saaty. La synthèse des matrices par paires est effectuée en déterminant les poids et les priorités.

Sur la base des informations disposées dans l'arbre des indicateurs, une synthèse supplémentaire est effectuée pour déterminer le classement relatif des alternatives. Les critères détaillés (qualitatifs et quantitatifs) sont comparés en utilisant des jugements éclairés ("je pense") pour déterminer les poids et les priorités. En utilisant des comparaisons par paires, il est facile d'exprimer l'importance relative d'un critère par rapport à un autre. La matrice est ensuite transformée en classement des critères. La détermination du vecteur propre permet d'obtenir des priorités à partir d'une matrice par paires.

Par la suite, La mesure de la cohérence aide à accepter ou à rejeter les matrices de l'AHP, car des jugements subjectifs sont portés sur la définition des matrices, ce qui peut entraîner une éventuelle incohérence. Il est donc nécessaire de vérifier la cohérence car c'est l'un des avantages les plus importants de l'AHP. Saaty suggère qu'un indice de cohérence inférieur ou égal à 0,10 indique que le décideur a correctement structuré le problème en question, mais si l'indice de cohérence est supérieur à 0,10, alors la réponse par sujet peut être considérée comme aléatoire.

### *Prise de décision*

L'évaluation de la performance durable de ces processus équivaut à l'évaluation de la performance des processus par rapport à tous ces critères. Un problème méthodologique se pose alors pour définir la stratégie décisionnelle qui conduit à une évaluation et à un choix. Afin de permettre au décideur de faire le bon choix, plusieurs méthodes ont été développées dans le contexte multicritères depuis les années 1960. Ces méthodes permettent alors d'orienter le décideur vers un compromis judicieux plutôt que vers un optimum souvent dépassé (BenMena, 2000). Un très grand nombre de méthodes multicritères peuvent être identifiées, ce qui peut être considéré comme une force ou une faiblesse (Bouyssou et al., 1993). Cette multiplicité des méthodes d'agrégation s'explique par le fait qu'aucune méthode ne répond complètement aux besoins attendus par l'utilisateur (Schärlig, 1985). Ainsi, en fonction de la manière dont les performances sont agrégées, les analystes devront adapter leurs approches. Cependant, la plupart de ces méthodes appartiennent à l'une des trois approches opérationnelles suivantes (Roy et Giard, 1985): l'approche de synthèse à critère unique; l'approche de surclassement de la synthèse; l'approche du jugement local interactif avec des itérations par tâtonnements. Dans le cadre de ce travail de recherche, nous avons choisi de nous placer dans le cadre de l'approche de synthèse à critère unique afin d'évacuer toute incomparabilité. Les préférences sont ensuite introduites a priori. Elles sont agrégées en une seule fonction (valeur, utilité) qui est ensuite optimisée. Les principales méthodes appartenant à cette approche sont les suivantes: Somme pondérée, MAUT (Fishburn, 1970; Vincke, 1989), SMART (Edwards, 1971), UTA (Jacquet-Lagreze et Siskos, 1982), TOPSIS (Hwang et Yoon, 1981), AHP (Saaty, 1980) et G.P (Ignizio, 1978).

Ainsi, le processus décisionnel de l'AHP passe par les principales étapes suivantes: détermination de l'analyse matricielle par paires, jugement de la matrice de comparaison, détermination des vecteurs prioritaires et de la valeur propre maximale, vérification de la cohérence et enfin calcul de la comparaison complète des critères. La formulation mathématique est généralement présentée et ajustée chaque fois que le niveau change. Une matrice carrée (A) de taille n pour chaque niveau et la matrice normalisée correspondante, ainsi que le vecteur de pondération des critères. De même, pour la vérification de la cohérence, l'indice de cohérence moyen proposé par (Saaty et Vargas, 2012) est utilisé comme indiqué dans le tableau 6.2.

La prise de décision finale repose sur un vote préférentiel de Borda, dans lequel l'électeur déclare un classement des candidats par ordre de préférence. La méthode de vote Borda détermine le vainqueur d'une élection en donnant à chaque candidat, un nombre de points correspondant au nombre de candidats classés au bas de l'échelle. Elle considère que la préférence de vote permet d'identifier au moins le meilleur compromis possible et que, tout au plus, la sagesse collective ne devrait pas imposer un système de vote, comme une procédure contradictoire dans laquelle la majorité gagne tout alors que la minorité ne gagne rien (Emerson, 2013). Cela signifie que cette méthode tend à privilégier les candidats largement acceptables, plutôt que ceux soutenus par la majorité.

Dans la méthode de comptage de Borda appliquée dans cette étude, les préférences sont attribuées en tant que premier, deuxième, dernier ( $n, n-1, \dots, 1$ ) ou plus fréquemment ( $n-1, n-2, \dots, 0$ ). Toutefois, dans le cas où une ou plusieurs personnes soumettent un vote partiel, les résultats peuvent varier considérablement. Les informations nécessaires pour appliquer le décompte Borda sont les classements comme premier, deuxième, ..., dernier et la fréquence des préférences ou le nombre de fois que chaque préférence est mentionnée.

La mesure de la performance durable tient compte d'un maximum d'informations concernant les ensembles d'indicateurs de performance. Les principaux critères sont le confort, le coût, la qualité, la performance durable, la flexibilité, le style, le délai de mise sur le marché, les déchets, etc. En outre, l'autorisation de mise sur le marché qui garantit que le produit est sûr pour la santé humaine et l'environnement pendant son utilisation et qu'il ne crée pas de risques pour la santé, la sécurité et le travail pendant la fabrication ou après l'utilisation. La collecte de données se fait par la collecte de mesures quantitatives auprès des concepteurs et des fabricants, en complétant les avis des experts et l'enquête bibliographique. Enfin, la structuration des ensembles d'indicateurs est organisée en fonction des 38 indicateurs les plus préférés (sous-critères) parmi les 68 indicateurs de performance durable proposés.

### *Cas d'application*

La démarche est appliquée au cas de la fabrication d'éléments de visière dans le cadre de la pandémie Covid-19. Ainsi, Sigma Clermont a décidé de fabriquer trois supports d'écran facial différents en utilisant le moulage par injection, l'impression 3D et la découpe laser, comme le montre la figure 6.2, en partenariat avec les lycées Jean Zay et Germaine Tillon de Thiers. La production de ces pièces dans différents ateliers nécessitent une connaissance appropriée de la procédure de conception, l'inclusion de caractéristiques obligatoires afin de ne pas compromettre la qualité attendue, l'efficacité de la protection (bien adaptée à l'objectif) et la nécessité de tenir compte des aspects de performance durable de la fabrication et de l'utilisation de ces produits.

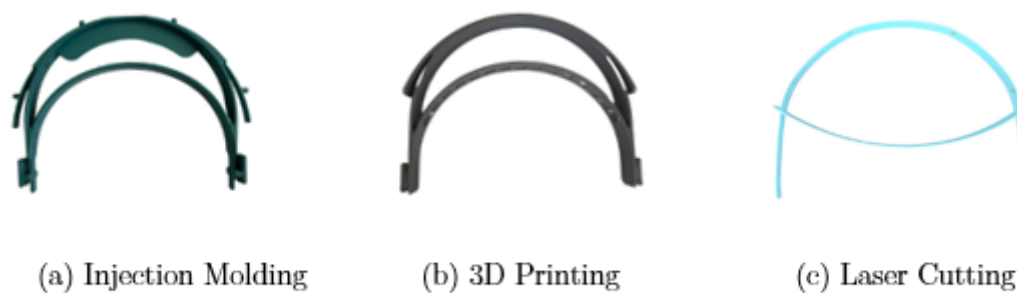


Figure 6.2 Faceshield brackets, Manufactured by Sigma Clermont

Ainsi, la question est d'évaluer la performance en matière de performance durable de la fabrication additive, en comparaison avec les autres procédés. Parmi les 68 indicateurs, la sélection de 38 indicateurs pour cette étude est faite sur la base de la pertinence et de l'impact immédiat pour une performance durable de chacun des trois procédés de fabrication. Après avoir identifié les indicateurs de performance de performance durable (SPI) ou les sous-critères pertinents, la pondération est effectuée en utilisant la méthode AHP. Le tableau 6.3 représente la catégorie des sous-critères et des sous-sous-critères sélectionnés pour chacun des trois critères de performance durable. Les indicateurs environnementaux concernent les critères relatifs aux matériaux, à l'énergie, aux émissions, à la conformité et au transport. Les indicateurs économiques concernent les critères de viabilité, de présence sur le marché et d'impact indirect. Les indicateurs sociaux concernent les critères d'emploi, de santé, de formation, de service et d'étiquetage des produits et de gouvernance.

Tableau 6.3 Catégorie de SPI inclus pour le cas sélectionné

Sustainability criteria	Subcriteria	Sub-subcriteria
Environment ( $C_1$ )	Material ( $SC_1$ )	Consumption ( $SSC_1$ )
		Efficiency ( $SSC_2$ )
		Availability ( $SSC_3$ )
		Value recovery ( $SSC_4$ )
	Energy ( $SC_2$ )	Consumption ( $SSC_5$ )
		Renewables ( $SSC_6$ )
	Emission, effluent and waste ( $SC_3$ )	GHG emission ( $SSC_7$ )
		Primary air pollutants ( $SSC_8$ )
		Secondary air pollutants ( $SSC_9$ )
		Waste ( $SSC_{10}$ )
	Conformance ( $SC_4$ )	Monetary values of fines ( $SSC_{11}$ )
		Nonmonetary sanctions ( $SSC_{12}$ )
		Expenditure ( $SSC_{13}$ )

Economic (C <sub>2</sub> )	Transport (SC <sub>5</sub> )	Impact (SSC <sub>14</sub> )
		Strategy (SSC <sub>15</sub> )
	Economic viability (SC <sub>6</sub> )	Value (SSC <sub>16</sub> )
		Cost (SSC <sub>17</sub> )
		Innovation (SSC <sub>18</sub> )
		Benefit plan (SSC <sub>19</sub> )
	Marketing presence (SC <sub>7</sub> )	Wages (SSC <sub>20</sub> )
		Suppliers (SSC <sub>21</sub> )
		Local community (SSC <sub>22</sub> )
	Indirect economic impact (SC <sub>8</sub> )	Investment (SSC <sub>23</sub> )
		Impact knowhow (SSC <sub>24</sub> )
Social (C <sub>3</sub> )	Employment (SC <sub>9</sub> )	Employment type (SSC <sub>25</sub> )
		Job creation (SSC <sub>26</sub> )
		Job security (SSC <sub>27</sub> )
		Performance (SSC <sub>28</sub> )
	Occupational health and safety (SC <sub>10</sub> )	Injury rate (SSC <sub>29</sub> )
		Risk (SSC <sub>30</sub> )
	Training and education (SC <sub>11</sub> )	Training (SSC <sub>30</sub> )
		Skill management (SSC <sub>31</sub> )
		Career development (SSC <sub>33</sub> )
	Product and service labeling (SC <sub>12</sub> )	Customer satisfaction (SSC <sub>34</sub> )
		Conformity (SSC <sub>35</sub> )
		Values (SSC <sub>36</sub> )
	Governance (SC <sub>13</sub> )	Equity and fairness (SSC <sub>37</sub> )
		Efficiency (SSC <sub>38</sub> )

Certains indicateurs ont été exclus. Cette exclusion se fonde sur le fait que soit l'indicateur n'a pas de pertinence directe pour l'évaluation des performances durables de ce cas spécifique, soit leur impact est similaire, selon le procédé envisagé. Les données collectées pour la sélection des indicateurs [annexe A] sont utilisées comme support pour l'exclusion des SPI, en se basant sur le fait que la contribution est égale ou qu'aucune donnée directe ne peut être obtenue pour d'autres processus. La liste des indicateurs de performance durable présentée à l'annexe A ne comprend pas les sous-critères de la dimension environnementale (eau, biodiversité et produits et services) et de la dimension sociale (marketing et communication et respect des normes sociales), qui sont entièrement exclus avant la collecte des données. L'exclusion de 16 SPI supplémentaires est effectuée sur le fait que leur impact immédiat sur l'évaluation de la performance durable pour le produit et les alternatives sélectionnés est soit égal, soit non pertinent.

La fabrication des supports de visière utilisés pour cette étude a été réalisée selon trois méthodes de fabrication: le moulage par injection (ALT<sub>1</sub>), l'impression 3D (ALT<sub>2</sub>) et la découpe laser



(ALT<sub>3</sub>). Chaque procédé est basé sur une application, un type de matériau et des exigences spécifiques. Le processus de hiérarchie analytique (AHP) est utilisé pour l'analyse décisionnelle multicritères et l'évaluation agrégée des indicateurs qui implique la définition de l'arbre de décision, la matrice de jugement de comparaison et le calcul des critères agrégés, des sous-critères, des sous-sous-critères et des alternatives. Les auteurs ont utilisé certains aspects du cadre général d'évaluation de la performance durable des processus de fabrication, tel que proposé par (Saad et al., 2019) qui se concentre au niveau du produit.

Le moulage par injection (première méthode, ALT<sub>1</sub>) nécessite une presse et une conception spécifique du moule avant la fabrication. Il est mis en œuvre par des entreprises spécialisées qui ont réalisé des investissements importants, car ce procédé repose sur une haute technicité. Les principaux avantages de cette méthode sont la possibilité de produire un support en 1,2 minute (le plus rapide) et permet de le fabriquer avec un excellent état de surface et de meilleures propriétés mécaniques. Le procédé est compétitif en terme de coût pour la production en série. L'inconvénient évident est que sa mise en œuvre demande plus de temps et que la modification de la pièce est coûteuse puisqu'elle nécessite la conception d'un nouveau moule. Au cours de cette étude, la conception et la fabrication des moules ont nécessité 3 jours de travail. Même une modification mineure nécessite le même temps. La performance durable du moulage par injection dépendent fortement de l'utilisation des matières premières, de la conception du moule et des paramètres de processus associés pour évaluer le taux de production, le coût global du produit, l'efficacité et la précision dimensionnelle (Barbosa et al., 2018).

En injection plastique, certains portefeuilles de matériaux comprennent le polycarbonate (PC), l'acrylonitrile-butadiène-styrène (ABS), le polypropylène (PP), le polytéréphtalate de butylène (PBT) (Singh et Verma, 2017). Les principaux paramètres du processus sont la température de fusion, le temps d'injection et d'emballage, le temps de refroidissement ou de maintien et la pression d'injection (Barbosa et al., 2018; Singh et Verma, 2017). En fonction de la variation de ces paramètres, il est possible de minimiser les défauts courants tels que le gauchissement, le rétrécissement, l'ondulation de la surface, la rugosité et les lignes de joint. De plus, le type de matière première, la conception du moule et les variables de traitement appropriées permettront une production rapide, peu coûteuse, efficace et une précision dimensionnelle conforme des composants complexes.

L'évaluation de l'impact environnemental de la phase d'utilisation du produit est faible en raison du manque de données sur l'inventaire du cycle de vie. La consommation d'électricité pendant la fabrication peut être prise en compte. En ce qui concerne les émissions de gaz à effet de serre (GES), pour 1 kg de PBT recyclé, la contribution est dominée par les matières premières (jusqu'à 45 %) et suivie par la fabrication (38 %), l'emballage secondaire (5 %), le transport (3 %) et les étapes de fin de vie (9 %). Ce pourcentage varie en fonction du type de matériau utilisé, les

matériaux recyclés affichant une baisse significative (jusqu'à 24 %) lorsque la fabrication est effectuée à partir de 100 % de contenu recyclé (Dormer et al., 2013). Le moulage par injection de plastique augmente les émissions indirectes de carbone en raison de la forte consommation d'électricité lors de la fabrication (Rajemi et Hassan, 2015).

La deuxième méthode (ALT<sub>2</sub>) est l'impression 3D qui donne un support très léger, très souple et aux propriétés mécaniques relativement moindres que le support de visière fabriqué par moulage par injection. Comme la fabrication se fait directement à partir du modèle CAO, cette alternative est la moins chère à fabriquer ainsi qu'à modifier. L'inconvénient est qu'elle est la plus longue (140 minutes pour un seul support) et qu'elle convient à une production à petite échelle. En général, l'impression 3D est un procédé de fabrication par dépôt fondu (FDM) ou de fabrication de filaments fondus (FFF) où une buse chauffée fait fondre des matériaux thermoplastiques. Un filament thermoplastique solide est forcé à travers une buse d'extrusion chauffée, fondu et déposé pour former des objets destinés à diverses applications dans des pièces industrielles ou médicales (Azimi et al., 2016 ; Bravi et al., 2019 ; Byrley et al., 2020 ; Davis et al., 2019).

Les matériaux filamentaires les plus courants utilisés par l'impression 3D pour la construction d'objets couche par couche comprennent l'acide polylactique (PLA), le polyuréthane thermoplastique (TPU), le nylon, l'ABS et le PC, qui peuvent souvent être mélangés à des colorants et à d'autres additifs (Davis et al., 2019). Le PLA est un plastique biodégradable à base de maïs qui permet d'imprimer à des températures de buse allant jusqu'à 1800°C et à des températures de plaque de base proches de la température ambiante. Le thermoplastique PLA biodégradable est dérivé de ressources végétales renouvelables, principalement de l'amidon et du sucre. L'avantage du PLA est qu'il est compostable et qu'il provient de sources renouvelables. Il contribue à atténuer les problèmes d'élimination des déchets solides et à réduire la dépendance des matériaux d'emballage aux plastiques à base de pétrole (Lim et al., 2008).

Le principal avantage de la fabrication additive est de permettre de nouvelles conceptions pour résoudre les contraintes de fabrication. Enfin et surtout, le fait d'avoir besoin de moins d'équipements et d'outillage augmente considérablement la viabilité économique de la production en petit volume et de la personnalisation (Huang et al., 2017). Mais comme inconvénient commun, (Byrley et al., 2020) rapporte que l'extrudeuse de filaments émet de grandes quantités de particules respirables ultrafines et divers composés organiques volatiles (COV). Il est évident que la quantité varie en fonction des opérations. Le processus de chauffage entraîne l'émission de gaz volatiles et de particules ultrafines (UFP) qui détériorent la qualité de l'air intérieur. Cette émission de COV dépend des types spécifiques de filaments utilisés en fonction des additifs de chaque filament. Par exemple, on a constaté que l'ABS libérait plus de COV totaux que le PLA. Certains COV possèdent des propriétés toxiques, irritantes et/ou odorantes. L'utilisation

à l'intérieur pendant entraîne une exposition aiguë et chronique des utilisateurs et des occupants environnants.

Selon (Davis et al., 2019 ; Khosravani et Reinicke, 2020), le fonctionnement à l'intérieur des imprimantes 3D s'avère être une source de nombreux COV et de particules qui peuvent être rejetés dans l'air intérieur, 216 COV individuels ayant été identifiés comme ayant un impact sur l'air intérieur et la santé humaine. L'émission globale de particules dépend du matériau des filaments, de la température de l'extrudeuse, de la couleur des filaments, du chauffage des plaques de construction et du modèle d'imprimante (Azimi et al., 2016). L'émission d'UFP lorsque les dimensions des particules sont inférieures à 100 nm et de COV dangereux varie en fonction du modèle d'imprimante, du type de filament, de la buse, de la température du lit et du temps d'impression. Les COV émis par l'ABS vont de 10 à 110µg/min et le PLA de 4 à 5 µg/min.

La troisième méthode (ALT<sub>3</sub>), la découpe au laser, utilise également une machine de grande dimension et des planches de PP. Cette méthode est un peu plus lente (1,25 minute pour un seul support) que le moulage par injection et elle convient également à la production à petite échelle. La découpe au laser étant réalisée dans un Fab Lab, la conception et la fabrication de pièces innovantes peuvent être réalisées par des particuliers. Il s'agit d'une technique de fabrication soustractive numérique à partir de fichiers DXF.

Les informations d'entrée nécessaires avant l'opération sont le motif, le type de matériau, les dimensions (épaisseur, forme). Le procédé permet de découper de fines feuilles de différents matériaux. Selon les dimensions de la plaque, un grand nombre de pièces peut être produit en même temps sans intervention humaine. Selon le matériau, de la fumée peut être produite. Ce procédé est facile d'accès, car il utilise des ressources communes qui sont facilement partagées. Le coût d'investissement d'une machine d'entrée de gamme est assez faible (entre 10 et 30 k€). Il faut noter que l'utilisation de ce procédé a nécessité une reconception de la pièce et une simplification des formes, pour transformer une pièce en 3D en un ensemble de pièces en 2D assemblées entre elles. La pièce obtenue est plus légère et moins résistante. Ainsi, ces caractéristiques placent l'accessibilité de ce procédé entre le moulage par injection et l'impression 3D.

Ainsi, nous comparons trois procédés aux caractéristiques très différentes: un procédé très industriel et deux procédés destinés au grand public. En effet, la question de la diffusion des moyens de production est importante dans le cadre de l'Industrie 4.0.

Tableau 6.5 Caractéristiques importantes des trois processus

Feature	Injection Molding	3D Printing	Laser Cutting
Material	PP	PLA	PP
Material Format	Pellet	Filament	Plate
Material Cost	2,13 €/ Kg	30 € / Kg	5,88 € /g
Weight / part	36 g	32 g	13 g
Waste / part	0 g	4 g	1,5 g
Manufacturing time	1 min 12 s / part	140 minutes / part	1 min 25 s / part
Machine Cost	20 € / h	1 € / h	5 € / h
Energy consumption	500 Wh	375 Wh	52 Wh
Skill	Important Operator training 3 days Technician training 1 year	Weak	Medium Operator training 30 min Technician training 2 days
Investment	Need an industrial infrastructure of large machine tool	There is no need for infrastructure	Structure like Fab Lab has to be developed

Le tableau 6.5 présente certaines caractéristiques importantes pour les trois processus, utilisées pour aider les décideurs à porter des jugements dans des comparaisons alternatives où les jugements sont associés aux matériaux utilisés, au poids du produit, au temps de fabrication, au coût et à la formation nécessaire pour l'amélioration des compétences.

#### *Contribution des sous-critères*

Par la suite, il convient d'évaluer la contribution de chaque sous-critère aux trois dimensions de la performance durable: contribution aux dimensions environnementale, économique et sociale, respectivement.

La contribution des matériaux est structurée en fonction de la consommation de matériaux ( $SSC_1$ ), de l'efficacité des matériaux ( $SSC_2$ ), de la disponibilité ( $SSC_3$ ) et de la récupération des matériaux ( $SSC_4$ ). La consommation de matériaux fait référence à la quantité totale de matériaux consommés pour fabriquer un support d'écran, qui est approximée à partir du poids total du support fabriqué par chacun des trois processus. L'efficacité de l'utilisation des matériaux est obtenue en comparant le poids du support du poids total des matières premières achetées. La possibilité de déterminer/planifier le recyclage aide les déchets existants à réintégrer le système pour avoir une meilleure efficacité matérielle. La disponibilité des matériaux a également été évaluée. Les matières premières utilisées sont le propylène (PP) et l'acide polylactique (PLA). Ces matières premières permettent une mise en œuvre facile, un moulage et une impression plus rapides et moins de déchets. Le PP est utilisé pour le moulage par injection et la découpe laser, et le PLA pour l'impression 3D afin de fabriquer le support. Mais diverses alternatives pour

remplacer ces matériaux incluent l'ABS, le PETG, le TPU95, etc. selon la méthode de fabrication et l'application.

La contribution à l'énergie est déterminée sur la base de la consommation d'énergie ( $SSC_5$ ) et de l'utilisation d'énergie renouvelable ( $SSC_6$ ). La consommation d'énergie peut être considérée comme directe et indirecte. Dans la fabrication des pièces, l'énergie est consommée dans l'extraction, le traitement et le transport des matériaux (ce qui n'a pas été abordé dans cette étude) mais la consommation approximative d'énergie par machine est prise en compte. Pour fabriquer un seul support, l'impression 3D utilise une machine de 150W et fonctionne pendant 2,5 heures, soit une consommation d'énergie d'environ 0,375 KWh. Une machine de découpe laser utilise un tube laser (150W) et une puissance totale de 2,5KW, ce qui donne une consommation d'énergie de 0,052 KWh. Les consommations d'énergie liées au fonctionnement de la machine et au chauffage des matériaux sont donc d'un intérêt majeur. Utiliser un PP et un PLA recyclés, au lieu d'un intrant vierge, est plus intéressant pour minimiser la consommation d'énergie directe et indirecte.

L'effet des émissions, effluents et déchets (EEW) est essentiellement lié aux machines utilisées, au transport et au mécanisme d'élimination (Beng et Omar, 2014 ; Chatzisideris et al., 2016 ; Deutz et al., 2013 ; Dufrene et al., 2013 ; Giffi et al., 2014). Le secteur manufacturier a contribué à 19 % des émissions de GES (2013) dans l'activité économique des pays européens (Saad et al., 2019). Ainsi, les progrès technologiques contribuent à minimiser l'impact associé à l'EEW grâce à une consommation minimale d'énergie et de ressources. Les contributions des émissions de gaz à effet de serre (GES) ( $SSC_7$ ), des polluants atmosphériques primaires, des PAP ( $SSC_8$ ), des polluants atmosphériques secondaires, des SAP ( $SSC_9$ ) et des déchets ( $SSC_{10}$ ) sont considérées dans cette catégorie.

Les polluants principaux (PAP) sont apportés sous forme d'émissions directes telles que le  $CO_2$ , les  $SO_x$ , le CO et les PM, les COV, etc. et les polluants secondaires (PAS) tels que le smog, le  $SO_2$  et d'autres polluants proviennent des NOX et des COV. Le chauffage des PAP à une température supérieure à 2000°C peut être nocif pour la santé humaine et plus de 216 COV individuels sont rejetés dans l'air intérieur (Bravi et al., 2019 ; Davis et al., 2019). Dans le moulage par injection, des émissions volatiles se produisent à partir des événements des cylindres et des moules de chauffage ou d'injection. Selon (Azimi et al., 2016), les températures de traitement et de décomposition les plus élevées pour le PP sont respectivement de 275°C et 300°C, mais les produits de décomposition ne se forment pas à la température de moulage par injection. À titre de référence, les COV émis par l'ABS et le HSPI vont de 10 à 110  $\mu\text{g}/\text{min}$  et le PLA de 4 à 5  $\mu\text{g}/\text{min}$  (Azimi et al., 2016). Le processus de moulage par injection génère des émissions environnementales élevées lors de la fusion à haute température. L'impression 3D en génère pendant l'extrusion du filament dans les plages de température de fusion de 200 °C à 318 °C

pour le PP. La sélection du matériau du filament est un indicateur des COV potentiels qui auraient un impact sur la santé humaine et les conditions de travail, comme une ventilation adéquate en cas de découpe au laser des plastiques, peuvent minimiser l'impact sur les opérateurs.

En ce qui concerne les déchets, pour la fabrication par moulage par injection, il y a très peu de déchets. Mais il y a un avantage à réutiliser les déchets de PP provenant du moulage par injection, ce qui réduit considérablement la contribution des déchets à l'environnement. Les matériaux utilisés dans les trois procédés sont recyclables et la production de déchets est limitée, environ 4 g pour l'impression 3D et 1,5 g pour la découpe laser par support d'écran. En outre, l'initiative visant à atténuer les impacts environnementaux peut être réalisée davantage par des économies d'énergie, notamment dans la préparation et le transport des matières premières.

La conformité est mesurée par la valeur monétaire des amendes pour non-conformité (SSC<sub>11</sub>), le nombre de sanctions non monétaires (SSC<sub>12</sub>) pour non-conformité aux réglementations environnementales et le total des dépenses et investissements en matière de protection de l'environnement (SSC<sub>13</sub>). Il existe une variation entre les matériaux en ce qui concerne la conformité aux normes sociales (Behrisch et al., 2011 ; Beng et Omar, 2014 ; Cor et al., 2014 ; Deutz et al., 2013). Le PLA est obtenu à partir de sources renouvelables et contribue moins aux impacts négatifs sur l'environnement et a moins de chance d'obtenir des amendes ou des sanctions non monétaires pendant la transformation. De plus, le traitement après utilisation pourrait être possible grâce au recyclage pour les deux matériaux.

Les transports tiennent compte des contributions de l'impact environnemental des produits de transport (SSC<sub>14</sub>) et de la stratégie d'introduction d'un mode de transport efficace (SSC<sub>15</sub>). Un dispositif d'impression 3D peut être mis en œuvre localement et rapprocher la fabrication des utilisateurs de produits, ce qui permet de raccourcir considérablement les chaînes d'approvisionnement et de réduire les coûts de logistique et de transport dans le domaine du CM (Badurdeen et Jawahir, 2017; Behrisch et al., 2011; Bereketli et Erol Genevois, 2013; Cobut et al., 2015; Cor et al., 2014; Deutz et al., 2013).

L'impact environnemental associé au transport comprend les matériaux et les matières premières. Le besoin élevé en infrastructures pour le moulage par injection exige le transport des matières premières jusqu'à l'usine de fabrication et des produits manufacturés jusqu'aux utilisateurs, ce qui laisse cet impact plus élevé que l'impression 3D qui peut être située soit chez le consommateur, soit à proximité de la source du matériau. Ainsi, au coût de la mise en place des infrastructures et des Fab Labs, il est également possible d'envisager un transport économe en énergie à proximité de l'utilisateur ou de la source du matériau.

Les sous critères économiques sont évalués. On considère les contributions de la valeur économique directe ( $SSC_{16}$ ) générée, le coût ( $SSC_{17}$ ) encouru tout au long du cycle de vie du produit, l'innovation ( $SSC_{18}$ ) comme une dépense de recherche et développement et le plan de bénéfices ( $SSC_{19}$ ) comme une éventuelle aide financière du gouvernement ou d'autres sources. Une évaluation peut être effectuée sur ces aspects du poids, de l'épaisseur, de la taille, de la forme et de la propriété des produits. La valeur économique des supports fabriqués par ces trois procédés dépend de l'échelle de production. La valeur économique la plus élevée va au moulage par injection suivi de la découpe au laser, puis à l'impression en 3D où elle est économiquement intéressante pour une production à petite échelle. L'impression en 3D offre de meilleures chances d'innovation et la possibilité d'obtenir une aide financière du gouvernement.

La contribution à la présence commerciale est considérée à partir des salaires standards d'entrée ( $SSC_{20}$ ), de la politique de dépenses sur les fournisseurs locaux ( $SSC_{21}$ ) et de l'embauche de la communauté locale ( $SSC_{22}$ ). Si l'on considère le développement des matériaux, la production de PLA utilisant un processus de fermentation peut faire appel à de nombreux fournisseurs locaux de matières premières. De plus, il est économiquement avantageux de centraliser la distribution à proximité des fournisseurs, ce qui minimisera les coûts et le temps passé en transport pour atteindre les clients.

L'impact économique indirect est mesuré par l'investissement ( $SSC_{23}$ ) et le service principalement au profit du public et l'impact du savoir-faire ( $SSC_{24}$ ) sur la création d'emplois par les fournisseurs, l'augmentation de la productivité et l'activité inter-entreprises. La fabrication additive aide à produire des pièces sur mesure ou des pièces comportant de multiples composants intégrés pour un meilleur bénéfice commercial. Elle encourage l'esprit d'entreprise et le développement de produits en réduisant au minimum les obstacles dus à la facilité de produire un prototype par simple impression dans un seul équipement. Elle encourage la création de produits personnalisés (Badurdeen et Jawahir, 2017; Vereinte Nationen, 2007).

Le moulage par injection nécessite une infrastructure industrielle significatives qui pourrait bénéficier au public par le biais d'un engagement commercial, en nature ou à titre bénévole ou d'intérêt public. Mais c'est plus cher que les installations de découpe laser qui nécessitent le développement de structures comme des Fab Lab, par rapport à l'impression 3D la moins chère où il n'est pas nécessaire de développer des infrastructures. Contrairement au moulage par injection qui est économiquement avantageux dans la production de masse, l'impression en 3D aura moins d'impact économique, notamment en termes d'emplois créés par les fournisseurs, d'amélioration de la productivité et d'activité inter-entreprises.

Les sous-critères sociaux sont aussi évalués. Le type de procédé a un impact sur le type et les performances requises de la main-d'œuvre en tant qu'employé (Chaim et al., 2018 ; Esty et al., 2005 ; Ghobadian et al., 2018 ; Holm, 2018 ; Zackrisson et al., 2017). Ainsi, la contribution à



l'emploi est déterminée à partir du type d'emploi de la main-d'œuvre totale (SSC<sub>25</sub>), des embauches de nouveaux employés et de la rotation du personnel en tant que création d'emplois (SSC<sub>26</sub>), de la sécurité et du confort de la main-d'œuvre par la sécurité de l'emploi (SSC<sub>27</sub>) et des performances (SSC<sub>28</sub>) en fonction des aptitudes, des connaissances et des compétences des employés.

*A priori*, la fabrication de supports ne nécessite pas d'autres types d'emplois que la conception de pièces de base et la mise en œuvre des machines.

En ce qui concerne la sécurité humaine due à l'émission de produits chimiques nocifs, la sécurité humaine (opérateur) n'est pas un problème dans la mesure où la fabrication est effectuée dans le cadre d'une ventilation adéquate. En cas de mauvaise ventilation, les fumées provenant de la découpe laser des plastiques affectent l'opérateur de la machine. Pour les trois procédés, les performances en matière d'emploi peuvent être facilement améliorées grâce à des formations d'opérateurs et de techniciens limitées à quelques jours. Il est également possible d'améliorer les performances par l'auto-apprentissage, par exemple en impression 3D.

Les principaux facteurs pris en compte pour la santé et la sécurité au travail (OHS) sont le taux d'accidents (SSC<sub>29</sub>), les blessures aiguës, les journées de travail perdues et les incidents de maladie, ainsi que l'éducation (SSC<sub>30</sub>) pour les programmes de prévention et de contrôle des risques. Le taux d'accidents est considérablement réduit dans les méthodes de fabrication additive puisqu'il n'y a pas d'implication continue des travailleurs pendant les activités de transformation et de post-transformation (Bereketli et Erol Genevois, 2013 ; Borchardt et al., 2011 ; Cohen et al., 2014 ; Eastwood et Haapala, 2015 ; Shojaeipour, 2015 ; Yuan et al., 2012). Ainsi, le risque de blessure ou de décès lié au travail est réduit au minimum dans l'impression 3D et la découpe laser par rapport au moulage par injection, qui a montré un taux de blessure croissant même chez les travailleurs expérimentés, principalement en raison de la formation et du non-respect des questions de sécurité telles que l'espacement, l'éclairage, le nettoyage, etc. Ainsi, des formations supplémentaires sont nécessaires pour le moulage par injection pour la sécurité. Par ailleurs, une amélioration des compétences pour l'impression 3D afin de stimuler l'innovation.

Les heures moyennes de formation nécessaires (SSC<sub>31</sub>), les programmes de gestion des compétences pour un meilleur développement de carrière (SSC<sub>32</sub>) et les examens réguliers des performances et du développement (SSC<sub>33</sub>) sont des contributions analysées pour le sous-critère de formation et éducation. La réalisation du produit visé nécessite une formation et un enseignement pour l'amélioration d'une aptitude, d'une connaissance ou d'une compétence spécifique en fonction du type et du nombre total d'heures requises selon le type de processus de fabrication. Cette formation est également liée à l'employabilité continue et au développement de carrière et peut être dispensée en entreprise ou en autoformation.



L'étiquetage des produits et services (PSS) prend en compte la satisfaction du client (SSC<sub>34</sub>) par la sécurité, le confort, la meilleure valeur, la conformité (SSC<sub>35</sub>) aux besoins et aux valeurs du client (SSC<sub>36</sub>) pour la valeur monétaire des amendes pour non-conformité. La fabrication additive peut être plus proche des utilisateurs et peut facilement être construite localement plutôt que dans de grandes usines et le niveau de qualité ou de confort attendu par les utilisateurs dépend de leurs besoins mais, en fonction du type de processus, il est très pertinent de mesurer la flexibilité et l'adaptation du travail.

Les deux contributions considérées pour la gouvernance sont l'équité et la justice (SSC<sub>37</sub>) concernant l'égalité des droits et la liberté, et l'efficacité (SSC<sub>38</sub>) ou la performance d'un employé ou d'une équipe. En ce qui concerne le développement des matières premières (PLA) pour l'impression 3D, il y a un problème moral de dépenses pour les cultures destinées aux bioplastiques alors que beaucoup en ont besoin pour leur alimentation. Mais la facilité d'auto-apprentissage, le prix moins élevé et la flexibilité de l'impression participent à l'égalité des droits et la liberté pour l'innovation et la fabrication de produits. Comme méthode pour améliorer les performances d'un employé en une journée, la formation dans l'entreprise pour le moulage par injection et la découpe laser mais l'autoformation pour les imprimantes 3D est une opportunité à saisir.

Une fois les sous-critères identifiés et analysés, il convient d'en évaluer les contributions. L'arbre des indicateurs classe le problème en commençant par l'objectif de performance durable représenté au niveau le plus élevé jusqu'aux contributions au niveau le plus bas (figure 6.4). Les trois alternatives sont indiquées au niveau le plus bas de la hiérarchie. L'arbre des indicateurs comprend quatre niveaux hiérarchiques. Tout d'abord, l'objectif ou le but du problème est défini comme assurant la performance durable. Le niveau 1 compare les trois critères (environnement, dimensions économiques et sociales) à l'objectif. Le niveau 2 compare les sous-critères sélectionnés par rapport aux critères. Le niveau 3 compare chaque sous-critère aux sous-critères et enfin le niveau 4 contient les trois alternatives liées aux sous-critères. L'objectif de chaque analyse est de cibler le meilleur critère et la meilleure alternative par rapport au niveau hiérarchique supérieur.

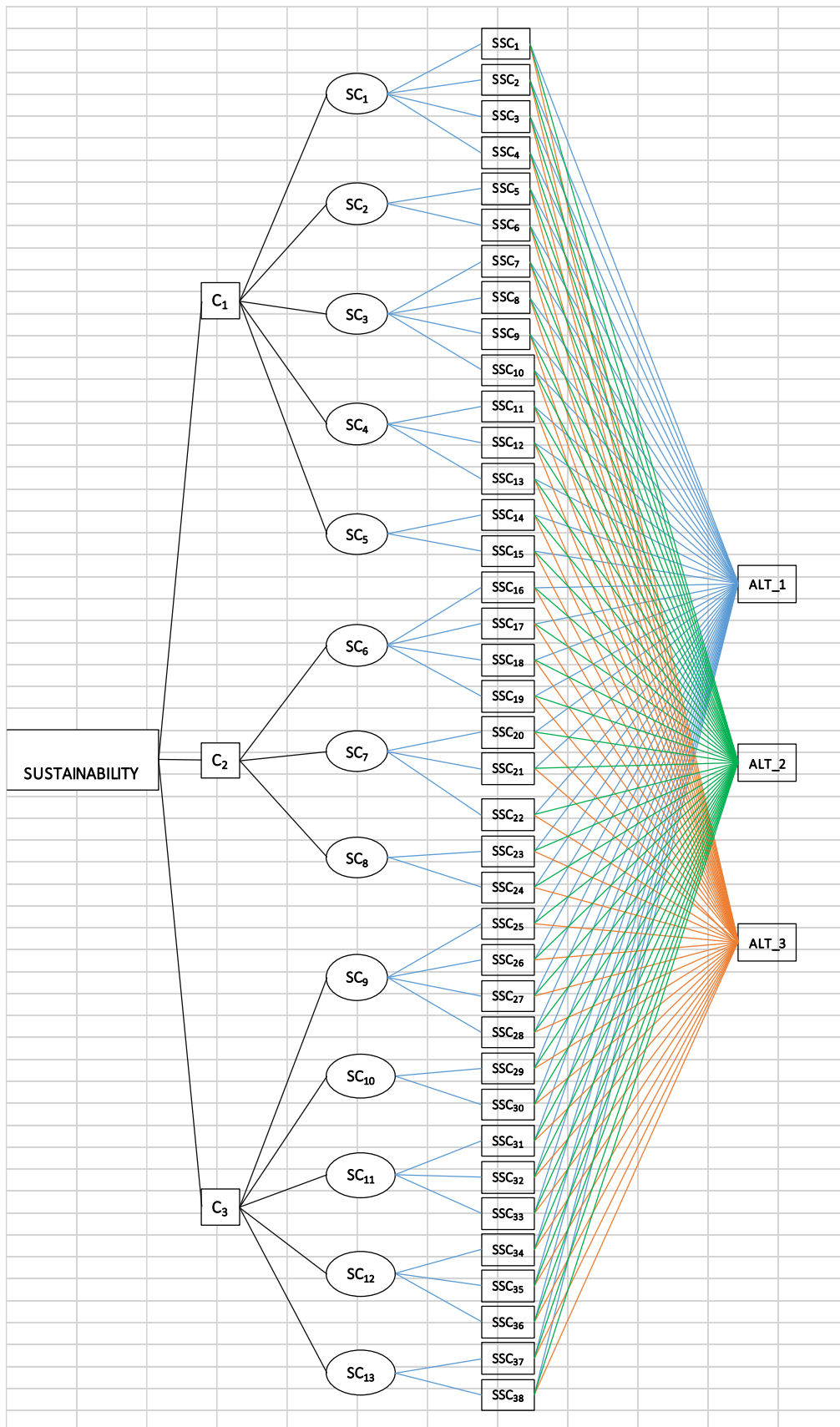


Figure 6.4 Arbre des indicateurs - Une hiérarchie à quatre niveaux [proposé par les auteurs]

*Analyse AHP*

Par la suite, l'objectif de l'analyse AHP est d'évaluer la performance durable de trois méthodes de fabrication des supports. La détermination des valeurs de comparaison pour les trois critères ( $C_1$  à  $C_3$ ), les treize sous-critères ( $SC_1$  à  $SC_{13}$ ), les trente-huit sous-critères ( $SSC_1$  à  $SSC_{38}$ ) et les trois alternatives ( $ALT_1$  à  $ALT_3$ ) a été effectuée sur la base de l'échelle de comparaison fondamentale présentée dans le tableau 6.1. Trois sous-sous-critères représentatifs de chaque dimension de la performance durable ( $SSC_1$ ,  $SSC_{17}$  et  $SSC_{31}$ ) sont choisis pour montrer comment les jugements sur les alternatives sont faits pour les SPI (sous-sous-critères) sélectionnés.

Consommation de matières ( $SSC_1$ ): La consommation de matériaux est calculée approximativement à partir du poids total des supports de l'écran. Ainsi, pour le  $SSC_1$ , les décideurs considèrent que le jugement est égal pour  $ALT_1$  et  $ALT_2$  puisque les poids des pièces fabriqués par les deux procédés sont de 36g et 32g et n'ont pas montré une grande variation (l'intensité d'importance se situe dans la plage d'importance égale). Mais par rapport à ces deux procédés, le support de visière fabriqué par  $ALT_3$  pèse 13g, ce qui est le poids le plus faible et pour  $SSC_1$ , c'est l'alternative préférée. Le niveau d'importance du tableau de comparaison donne une importance forte pour  $ALT_1$  et une importance modérée pour  $ALT_3$ .

Coût économique ( $CSD_{17}$ ): Le jugement porté sur le coût économique est basé sur le coût de chaque machine utilisée pour les trois alternatives. Par rapport à  $ALT_1$ , le coût des machines pour  $ALT_3$  est inférieur et même très inférieur pour  $ALT_2$ . D'après les informations recueillies,  $ALT_2$  coûte environ 3 000 euros et  $ALT_3$  environ 15 000 euros. Toutefois, cela ne signifie pas qu'il existe un taux de production et une valeur économique équivalents pour la pièce, le coût économique initial est important pour les utilisateurs. Par conséquent, sur la base de cette compréhension, on attribue à  $ALT_1$  une valeur plus élevée qu'à  $ALT_2$  et  $ALT_3$  avec une intensité d'importance 8 et 3 respectivement. En revanche,  $ALT_3$  se voit attribuer une valeur de forte importance (intensité de 5).

Gestion des compétences ( $SSC_{31}$ ): Le nombre moyen d'heures de formation et d'éducation pour compétence spécifique nécessaire ( $SSC_{31}$ ) varie selon le type de processus de fabrication. En outre, la formation est plus nécessaire pour l' $ALT_1$  que pour l' $ALT_3$  et l' $ALT_2$  respectivement. La formation nécessaire pour l' $ALT_2$  n'est pas obligatoire. Ainsi, sur la base de ces informations, les décideurs ont préféré l' $ALT_1$  avec une forte importance par rapport à l' $ALT_2$  et une importance modérée par rapport à l' $ALT_3$ . En outre, l' $ALT_3$  est préféré à l' $ALT_2$  avec une importance modérée.

Ainsi, une comparaison par paire à chaque niveau est effectuée. Les comparaisons donnent lieu à une matrice de jugement. L'importance relative est exprimée sur la base de l'échelle de comparaison fondamentale de Saaty. Les valeurs numériques représentent l'intensité de

l'importance sur une échelle de 0 à 9. La mesure de cohérence permet de vérifier la cohérence des jugements. Une autre information importante est l'indice de cohérence (IC) d'une matrice de comparaison, également connu sous le nom de variance de l'erreur commise lors de l'estimation. Le tableau 6.8 recense les inter-comparaisons des critères.

Tableau 6.8 Tableau comparatif des critères

Goal	Comparison	Preference	Importance	Evaluation
C <sub>1</sub>	SC <sub>1</sub> / SC <sub>2</sub>	SC <sub>1</sub> /SC <sub>2</sub>	Equal	1
	SC <sub>1</sub> / SC <sub>3</sub>	SC <sub>1</sub>	Very, very strong	8
	SC <sub>1</sub> / SC <sub>4</sub>	SC <sub>1</sub>	Very, very strong	8
	SC <sub>1</sub> / SC <sub>5</sub>	SC <sub>1</sub>	Moderate plus	4
	SC <sub>2</sub> / SC <sub>3</sub>	SC <sub>2</sub>	Very, very strong	8
	SC <sub>2</sub> / SC <sub>4</sub>	SC <sub>2</sub>	Very, very strong	8
	SC <sub>2</sub> / SC <sub>5</sub>	SC <sub>2</sub>	Weak	2
	SC <sub>3</sub> / SC <sub>4</sub>	SC <sub>3</sub> /SC <sub>4</sub>	Equal	1
	SC <sub>3</sub> / SC <sub>5</sub>	SC <sub>5</sub>	Very strong	1/7
	SC <sub>4</sub> / SC <sub>5</sub>	SC <sub>5</sub>	Very strong	1/7
C <sub>2</sub>	SC <sub>6</sub> / SC <sub>7</sub>	SC <sub>6</sub>	Very strong	7
	SC <sub>6</sub> / SC <sub>8</sub>	SC <sub>6</sub>	Moderate plus	4
	SC <sub>7</sub> / SC <sub>8</sub>	SC <sub>8</sub>	Moderate	1/3
C <sub>3</sub>	SC <sub>9</sub> / SC <sub>10</sub>	SC <sub>9</sub> /SC <sub>10</sub>	Equal	1
	SC <sub>9</sub> / SC <sub>11</sub>	SC <sub>9</sub>	Moderate	3
	SC <sub>9</sub> / SC <sub>12</sub>	SC <sub>9</sub>	Strong	5
	SC <sub>9</sub> / SC <sub>13</sub>	SC <sub>9</sub>	Strong	5
	SC <sub>10</sub> / SC <sub>11</sub>	SC <sub>10</sub>	Moderate	3
	SC <sub>10</sub> / SC <sub>12</sub>	SC <sub>10</sub>	Strong plus	6
	SC <sub>10</sub> / SC <sub>13</sub>	SC <sub>10</sub>	Strong plus	6
	SC <sub>11</sub> / SC <sub>12</sub>	SC <sub>11</sub>	Strong	5
	SC <sub>11</sub> / SC <sub>13</sub>	SC <sub>11</sub>	Moderate	3
	SC <sub>12</sub> / SC <sub>13</sub>	SC <sub>12</sub>	Moderate	3

Les tableaux de comparaison des critères sont transformés en matrices de jugements qui sont élaborées en transcrivant les valeurs de jugement du tableau 6.8 pour les trois dimensions de la performance durable. Le processus se poursuit pour l'inter-comparaison des sous-critères.

#### *Comparaison des alternatives*

Le processus de comparaison concerne aussi les alternatives entre les 3 procédés. Pour ce problème, les trois procédés de fabrication alternatifs envisagés sont analysés. Sur l'arbre hiérarchique de la figure 6.4, ces alternatives se situent au quatrième niveau comme le moulage

par injection (ALT<sub>1</sub>), l'impression 3D (ALT<sub>2</sub>) et la découpe laser (ALT<sub>3</sub>). Les approches d'adaptation des données collectées à partir des parenthèses fabriquées, les jugements des experts sont présentés dans le tableau 6.14, les jugements comparatifs par paires proposés par les décideurs tels qu'appliqués pour chaque sous-sous-critère sur la base des données des fabricants, de l'enquête bibliographique et de l'expérience.

Tableau 6.14 Jugement des décideurs sur les 3 alternatives

SPI	ALT <sub>1</sub> / ALT <sub>2</sub>			ALT <sub>1</sub> / ALT <sub>3</sub>			ALT <sub>2</sub> / ALT <sub>3</sub>		
	Preference	Importance & Evaluation		Preference	Importance & Evaluation		Preference	Importance & Evaluation	
SSC <sub>1</sub>	ALT <sub>1</sub> /ALT <sub>2</sub>	Equal	1	ALT <sub>3</sub>	Strong	1/5	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>2</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>3</sub>	ALT <sub>2</sub>	Moderate	1/3	ALT <sub>1</sub>	Moderate	3	ALT <sub>2</sub>	Strong	5
SSC <sub>4</sub>	ALT <sub>2</sub>	Moderate	1/3	ALT <sub>1</sub>	Weak	2	ALT <sub>2</sub>	Moderate	3
SSC <sub>5</sub>	ALT <sub>1</sub> /ALT <sub>2</sub>	Equal	1	ALT <sub>1</sub>	Exreme	9	ALT <sub>2</sub>	Very strong	7
SSC <sub>6</sub>	ALT <sub>2</sub>	Moderate plus	1/4	ALT <sub>3</sub>	Moderate	1/3	ALT <sub>2</sub>	Weak	2
SSC <sub>7</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Strong	5	ALT <sub>3</sub>	Weak	1/2
SSC <sub>8</sub>	ALT <sub>2</sub>	Very strong	1/7	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong plus	6
SSC <sub>9</sub>	ALT <sub>2</sub>	Very strong	1/7	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong plus	6
SSC <sub>10</sub>	ALT <sub>2</sub>	Strong plus	1/6	ALT <sub>1</sub> /ALT <sub>3</sub>	Equally	1	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>11</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>12</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>13</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>14</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>15</sub>	ALT <sub>2</sub>	Very strong	1/7	ALT <sub>3</sub>	Moderate plus	1/4	ALT <sub>2</sub>	Moderate	3
SSC <sub>16</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>17</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>18</sub>	ALT <sub>2</sub>	Extreme	1/9	ALT <sub>3</sub>	Strong plus	1/6	ALT <sub>2</sub>	Moderate	3
SSC <sub>19</sub>	ALT <sub>2</sub>	Strong plus	1/6	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>20</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Weak	2	ALT <sub>3</sub>	Strong plus	1/6
SSC <sub>21</sub>	ALT <sub>2</sub>	Moderate plus	1/4	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>22</sub>	ALT <sub>2</sub>	Strong plus	1/6	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong plus	6
SSC <sub>23</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>24</sub>	ALT <sub>2</sub>	Strong	1/5	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong	5
SSC <sub>25</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>26</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>27</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>28</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>1</sub>	Weak	2	ALT <sub>3</sub>	Strong	1/5
SSC <sub>29</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>30</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>31</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>32</sub>	ALT <sub>1</sub>	Moderate	3	ALT <sub>1</sub>	Strong plus	6	ALT <sub>2</sub>	Moderate	3
SSC <sub>33</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>34</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>3</sub>	Weak	1/2	ALT <sub>3</sub>	Strong	1/5
SSC <sub>35</sub>	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>2</sub>	Weak	2
SSC <sub>36</sub>	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>1</sub>	Weak	2	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>37</sub>	ALT <sub>2</sub>	Moderate plus	1/4	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>38</sub>	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>1</sub>	Strong plus	6	ALT <sub>2</sub>	Moderate	3

Le vecteur priorité est alors calculé à partir des matrices de jugements déduites, afin de vérifier la cohérence.

L'agrégation finale se fait en trois étapes. La première étape considérée est une agrégation des trois critères ( $C_1$ ,  $C_2$  et  $C_3$ ) avec les treize sous-critères ( $SC_1$  à  $SC_{13}$ ). Ensuite, l'agrégation des sous-critères avec les trente-huit sous-critères ( $SC_1$  à  $SC_{38}$ ) est effectuée. La troisième et dernière étape de l'agrégation se fait entre chacun de ces sous-sous-critères dans les trois alternatives (ALT\_1, ALT\_2 et ALT\_3). Les résultats de ces agrégations sont présentés dans les tableaux 6.17 à 6.19.

Le tableau 6.20 présente les résultats de l'analyse de la performance environnementale des trois alternatives (ALT<sub>1</sub>, ALT<sub>2</sub> et ALT<sub>3</sub>) pour les cinq sous-critères (matières, énergie, émissions, effluents et déchets, conformité et transport) et les quinze sous-critères (SSC<sub>1</sub> - SSC<sub>15</sub>). Alors que la figure 6.22 représente les résultats de l'évaluation de la performance environnementale sur la base des cinq sous-critères et des quinze sous-critères.

Pour les matériaux, la première note va à la découpe laser (0,038), ce qui montre une meilleure performance et la plus grande contribution provient du SSC<sub>1</sub> (consommation de matériaux). En effet, l'utilisation de plaques minces et la disposition optimale des pièces sur celles-ci réduisent considérablement la consommation de matériau. La deuxième note est attribuée à l'impression 3D (0,033), dont la principale contribution provient de la récupération de la valeur des matériaux (SSC<sub>4</sub>). Enfin, la troisième note est attribuée au moulage par injection (0,027), dont la principale contribution est l'efficacité des matériaux (SSC<sub>2</sub>).

En ce qui concerne l'énergie, l'impression 3D (0,041) est classée première, la principale contribution provenant de la consommation d'énergie (SSC<sub>5</sub>), le moulage par injection (0,031) est classée deuxième, la principale contribution provenant de SSC<sub>5</sub> et la découpe au laser (0,012) est classé troisième, la principale contribution provenant de SSC<sub>5</sub>. L'énergie est le critère le plus différenciant, car la consommation des machines individuelles est faible.

Les émissions, les effluents et les déchets, l'impression 3D (0,006) montre de meilleures performances et le contributeur le plus important est le SSC<sub>10</sub> (déchets), le moulage par injection montre la deuxième meilleure performance (0,003) où la contribution majeure provient du SSC<sub>7</sub> (émissions de GES) et la troisième performance est enregistrée pour la découpe laser (0,018) où la contribution majeure provient du SSC<sub>10</sub> (déchets).

La performance du moulage par injection (0,006) est meilleure lorsque la contribution la plus importante provient de la SSC<sub>13</sub> (dépenses), la découpe au laser (0,003) est la deuxième meilleure performance lorsque la contribution la plus importante provient de la SSC<sub>13</sub> et l'impression 3D (0,001) est la dernière de la liste lorsque la contribution la plus importante provient de la SSC<sub>13</sub>.

Le transport, l'impression 3D (0,035) montre la meilleure performance et le contributeur le plus important est SSC<sub>15</sub> (stratégie de transport) et la deuxième meilleure performance du moulage par injection (0,027) où le contributeur le plus important est SSC<sub>15</sub> et la troisième meilleure performance la découpe laser (0,013) où le contributeur le plus important est SSC<sub>14</sub> (impact du transport). L'impression 3D permet une production locale qui réduit le transport, contrairement à la modélisation par injection.

Le tableau 6.21 présente les résultats de l'analyse des performances économiques des trois alternatives (ALT<sub>1</sub>, ALT<sub>2</sub> et ALT<sub>3</sub>) pour les trois sous-critères (viabilité économique, présence sur le marché et impact économique indirect) et les neuf sous-critères (SSC<sub>16</sub> - SSC<sub>24</sub>). Alors que la figure 6.23 représente les résultats de l'évaluation des performances économiques sur la base des trois sous-critères et des neuf sous-sous-critères. Les résultats montrent les effets suivants.

Pour la viabilité économique, l'impression 3D (0,151) montre une meilleure performance et la plus grande contribution provient du SSC<sub>19</sub> (plan de prestations), le moulage par injection (0,117) montre la deuxième meilleure performance où le plus grand contributeur est le SSC<sub>17</sub> (coût économique). La troisième meilleure performance est celle de la découpe laser (0,083), dont la contribution la plus importante provient de la SSC<sub>19</sub> (régime d'avantages sociaux). La viabilité économique est une performance cumulative mesurée sur la base de jugements portés sur la valeur économique, le coût, l'innovation et le plan de bénéfices et non pas seulement sur le coût économique des machines.

Pour la présence marketing, l'impression 3D (0,016) montre une meilleure performance et le plus grand contributeur est lié à la SSC<sub>22</sub> (communauté locale) alors que le moulage par injection (0,015) où le plus grand contributeur est lié à la SSC<sub>20</sub> (salaires) et la découpe laser (0,012) où la plus grande contribution provient de la SSC<sub>20</sub>, ont montré la deuxième la troisième meilleure performance.

En ce qui concerne l'impact économique indirect, le moulage par injection (0,060) affiche une meilleure performance et le principal contributeur est la SSC<sub>23</sub> (investissement), l'impression 3D (0,025) est la deuxième meilleure alternative où la plus grande contribution provient de la SSC<sub>23</sub> (savoir-faire en matière d'impact) et la découpe laser (0,021) est la troisième alternative où la plus grande contribution provient de la SSC<sub>23</sub> (investissement). La performance d'ALT<sub>1</sub> est meilleure parce que les jugements portés sur l'investissement sont plus intenses que ceux d'ALT<sub>2</sub> et d'ALT<sub>3</sub>. En outre, comme mentionné dans la section 3.2.3, le moulage par injection nécessite une infrastructure industrielle de grandes machines-outils, qui pourrait bénéficier au public par le biais d'un engagement commercial, en nature ou à titre bénévole ou d'intérêt public.

Le tableau 6.22 présente les résultats de l'analyse des performances sociales des trois alternatives (ALT<sub>1</sub>, ALT<sub>2</sub> et ALT<sub>3</sub>) pour les cinq sous-critères (emploi, SST, formation et éducation,

étiquetage et gouvernance des SSP) et les quatorze sous-critères ( $SSC_{25}$  -  $SSC_{38}$ ). Alors que la figure 6.24 représente les résultats de l'évaluation des performances économiques sur la base des cinq sous-critères et des quatorze sous-critères. Les résultats montrent les effets suivants.

Pour l'emploi, le moulage par injection (0,058) montre une meilleure performance où le  $SSC_{27}$  (sécurité de l'emploi) est le plus grand contributeur, la découpe laser (0,020) est la deuxième meilleure où le plus grand contributeur est de même  $SSC_{27}$  et l'impression 3D (0,007) est la troisième alternative où le plus grand contributeur est encore  $SSC_{27}$ . En effet, le moulage par injection suppose la création d'une entreprise dans un schéma classique, ce qui tend à sécuriser les emplois.

En ce qui concerne la santé et la sécurité au travail, le moulage par injection (0,062) présente de meilleures performances, la  $SSC_{29}$  (taux d'accidents) étant la plus importante, le découpage au laser (0,020) la plus importante contribution étant également la  $SSC_{29}$  et l'impression 3D (0,008) la troisième meilleure, la contribution la plus importante étant encore une fois la  $SSC_{29}$ . Pour la formation et l'éducation, le moulage par injection (0,027) est plus performant, la contribution la plus importante étant celle de la formation ( $SSC_{31}$ ), la découpe laser (0,010) est la deuxième meilleure, la contribution la plus importante étant à nouveau celle de la formation ( $SSC_{31}$ ) et l'impression 3D (0,005) est la troisième meilleure alternative, la contribution la plus importante étant celle de la formation ( $SSC_{31}$ ) et de la gestion des compétences ( $SSC_{32}$ ).

Pour l'étiquetage des produits et services, le moulage par injection (0,010) est plus performant, la contribution la plus importante étant celle de la  $SSC_{36}$  (valeurs), la découpe laser (0,007) est la deuxième meilleure solution, la satisfaction du client étant la plus importante ( $SSC_{34}$ ) et la  $SSC_{36}$  et l'impression 3D (0,002) est la troisième solution, la contribution la plus importante étant celle de la  $SSC_{34}$ , de la conformité ( $SSC_{35}$ ) et de la  $SSC_{36}$ . En ce qui concerne la gouvernance, l'impression 3D (0,007) montre de meilleures performances où la  $SSC_{37}$  (Équité et justice) est la plus grande contribution, le moulage par injection (0,004) où la plus grande contribution vient de l'efficacité ( $SSC_{38}$ ) et la découpe laser (0,002) où la plus grande contribution vient de la  $SSC_{37}$ .

#### *Performance durable globale*

Les résultats de la figure 6.25 montrent que pour l'environnement, l'impression 3D (0,108 ou 10,8%) est meilleure que la découpe injection (0,102 ou 10,2%) et que le moulage par laser (0,067 ou 6,7%). Le moulage par injection est plus économique (0,1922 ou 19,22%) que l'impression 3D (0,1916 ou 19,16%) et que la découpe laser (0,1162 ou 11,62%). Au niveau social, le moulage par injection (0,160 ou 16%) est meilleur que la découpe laser (0,060 ou 6%) et que l'impression 3D (0,030 ou 3%).



Ces résultats révèlent que pour l'environnement, l'impression 3D est plus performante et que la plus grande contribution provient de l'énergie ( $SC_2 = 0,041$  ou 4,1%). La contribution la plus faible provient de la conformité ( $SC_4 = 0,0007$  ou 0,07 %). En ce qui concerne la dimension économique, le moulage par injection (légèrement meilleur) et l'impression 3D présentent des performances presque égales, les contributions les plus importantes étant respectivement la viabilité économique ( $SC_1 = 0,117$  et  $SC_1 = 0,151$ ). La contribution la plus faible provient de l'impact économique indirect ( $SC_3 = 0,060$  et  $SC_3 = 0,025$ ), respectivement. Enfin, en ce qui concerne la dimension sociale, le moulage par injection présente de meilleures performances, la SST ( $SC_2 = 0,062$ ) étant le facteur le plus important. Le contributeur le moins important est la gouvernance ( $SC_5 = 0,004$ ). En outre, la figure 6.26 représente la performance durable globale des trois critères sur la base de l'approche du vote pondéré de Borda. Le classement selon le nombre de Borda est le moulage par injection (premier), la découpe au laser (deuxième), l'impression 3D (troisième) et le classement selon l'approche de la somme est le moulage par injection (premier), l'impression 3D (deuxième) et la découpe au laser (troisième).

## Conclusion

Dans cette étude, une méthode de prise de décision multicritères appelée "processus de hiérarchie analytique" est utilisée pour évaluer efficacement la performance durable de trois alternatives, le moulage par injection, l'impression 3D et la découpe laser utilisée pour fabriquer trois différents supports de visière. Sur la base de l'analyse, le moulage par injection montre une meilleure performance globale en matière de performance durable. La somme totale des notes d'approche pour le moulage par injection, l'impression 3D et la découpe laser est de 42.8, 32.9 et 24.2 et les notes basées sur la méthodologie de comptage Borda sont respectivement de 87, 69 et 72.

De même, la contribution de chaque sous-critère et sous-sous-critère individuel est calculée et les performances de performance durable de chaque méthodologie sont analysées. Sur la base de chaque dimension, pour l'environnement, l'impression 3D a montré une meilleure performance (score = 0,108), la contribution la plus importante provenant de l'énergie (score = 0,041). Pour les dimensions économique et sociale, le moulage par injection a obtenu des scores de 0,192 (19,2 %) et 0,160 (16 %), respectivement, la contribution la plus importante provenant de la viabilité économique avec un score de 0,117 (11,7 %) et pour la dimension sociale, la santé et la sécurité au travail est la contribution la plus importante avec un score de 0,062 (6,2 %).

Afin de prendre des décisions finales, la méthode de vote pondéré de Borda est introduite pour la comparaison avec la somme simple. Pour l'approche par la somme simple, les scores de chacun des 38 sous-critères sont ajoutés dans chaque dimension de la performance durable. Il en résulte des scores de 0,428 pour le moulage par injection (classé premier), 0,329 pour l'impression 3D (classé deuxième) et 0,242 pour découpe au laser (classé troisième). Mais comme la fréquence du classement de chaque alternative varie, l'introduction de la méthode de vote pondéré de Borda

aidera à prendre une décision. Parmi les 38 sous-critères, la fréquence des meilleures préférences pour le moulage par injection, l'impression 3D et la découpe laser était de 23, 13 et 2 pour le premier choix, de 3, 5 et 30 pour le deuxième choix et de 12, 20 et 6 pour le troisième choix respectivement. Ainsi, les scores de Borda sont obtenus en additionnant les produits de fréquence du premier choix par 3, du deuxième choix par 2 et du troisième choix par 1. Cette méthode permet d'éviter la simple prise en compte des options qui sont préférées par la majorité et donne la possibilité d'envisager de meilleures performances d'autres alternatives.

L'importance des résultats de l'analyse est utile pour évaluer la performance durable de produits similaires fabriqués par des méthodes de fabrication différentes, similaires aux trois méthodes utilisées pour cette étude. Pour cette étude, une évaluation du marché n'a pas été faite et certaines dimensions sociales pourraient avoir une performance différente qui peut être considérée pour des travaux futurs.

## **Chapitre 7: Conclusions et perspectives**

Cette étude vise principalement à proposer des solutions d'évaluation de la performance durable des produits manufacturés sur la base des lacunes identifiées dans la compréhension de la performance durable elle-même, de la prise en compte des indicateurs de performance et de la mauvaise méthodologie d'évaluation de la performance durable et des tendances connexes. Les études existantes montrent que la performance durable devrait être un concept qui va au-delà de l'analyse des performances environnementales des processus et systèmes de fabrication et qui doit également prendre en compte les performances socio-économiques, étant donné que plusieurs industries manufacturières sont actuellement confrontées à des priorités économiques et financières qui peuvent aller à l'encontre des dimensions environnementales et sociales.

L'assurance de la performance durable dépend largement du type de processus de fabrication. Le passage à la conception pour la fabrication additive a donné l'opportunité aux concepteurs et aux fabricants de réduire certaines contraintes liées à la fabrication. C'est le principal avantage des procédés de fabrication additive pour donner une flexibilité de conception sans coût supplémentaire. C'est l'avantage le plus important, mais pas le seul, des procédés de fabrication additive. Ainsi, la principale contribution de cette étude est l'analyse de la performance durable de la fabrication additive par comparaison avec les procédés conventionnels.

L'évaluation de la performance durable de la fabrication additive se fait en considérant les aspects du cycle de vie des produits qui incluent la pré-fabrication (sélection des matériaux et conception), la fabrication, l'utilisation et les activités de post-traitement et la logistique. Les résultats de l'analyse montrent que l'utilisation efficace des ressources, la minimisation des coûts en intégrant les fonctions sur les pièces, la valeur économique des machines nécessaires à l'investissement, l'assemblage, la manipulation des outils et l'automatisation de l'atelier, l'entrepôt, la formation des employés, la minimisation des déchets, l'amélioration des performances des employés, les stratégies de traitement en fin de vie, la satisfaction des clients et la confiance du public, le transport, l'avantage de l'emplacement, sont des opportunités majeures pour la fabrication additive par rapport aux processus conventionnels.

La deuxième contribution de cette étude est l'élaboration d'une liste complète d'indicateurs de performance durable (SPI) qui peuvent être facilement comparés aux normes et qui sont proposés sur la base d'une prise en compte équilibrée des trois dimensions dans la conception et la fabrication de produits d'ingénierie. Cela a été fait grâce à l'évaluation approfondie de la littérature sur des sujets tels que le niveau de subjectivité dans la compréhension de la performance durable, les considérations relatives au cycle de vie des produits, la quantification et la stratégie d'interprétation de chaque indicateur et la tendance d'utilisation pour diverses applications.

Cette étude a proposé un total de 68 indicateurs de performance durable qui sont classés en sous-critères de deuxième niveau et en sous-critères de troisième niveau (SPI). En conséquence, l'étude a proposé 18 catégories d'indicateurs de deuxième niveau, 8 pour l'environnement, 3 pour l'économie et 7 pour le social et 68 sous-catégories de troisième niveau dont 29 pour l'environnement, 9 pour l'économie et 30 pour le social. Pour chaque sous-catégorie, une interprétation détaillée, un modèle d'évaluation de chaque indicateur de la sous-catégorie ainsi que les données nécessaires sont indiquées. Enfin, la validation de l'exhaustivité de la liste proposée d'indicateurs de performance durable en considérant dix des ensembles d'indicateurs et des lignes directrices les plus largement utilisés.

Le processus de validation de l'exhaustivité a montré que les trois dimensions de la performance durable n'étaient pas prises en compte de manière égale et que la dimension sociale était moins prise en compte que les dimensions économique et environnementale de la performance durable.

La troisième contribution de cette étude est le développement d'une nouvelle approche d'évaluation de la performance durable de la fabrication d'un produit d'ingénierie en utilisant la méthodologie de prise de décision multicritères. La méthodologie est proposée pour décrire, analyser, évaluer et optimiser formellement des indicateurs de performance durable conflictuels (critères) en sélectionnant une application de la fabrication de supports de visière. La méthodologie AHP est appliquée à l'évaluation durable de trois processus (moulage par injection, impression 3D et découpe laser) utilisés pour la fabrication des supports de visière. Sur la base de cette analyse, le moulage par injection montre une meilleure performance globale en matière de performance durable. L'analyse a également permis d'identifier la contribution de chaque sous-critère et sous-sous-critère individuel.

Les conclusions de cette étude participent certainement à une contribution politique supplémentaire, à des applications pratiques ou à des recherches ultérieures. Il s'agit notamment:

- De la création d'une compréhension commune de la performance durable et un ensemble d'indicateurs de performance durable afin d'éviter une prise en compte incomplète et subjective des indicateurs de performance;
- De la sélection des procédés de fabrication doit être fondée sur une évaluation appropriée des performances en matière de performance durable;
- Du potentiel de performance durable de la fabrication additive pour produire des formes complexes, des formes proches du fini, des pièces multifonctionnelles, légères, et les possibilités associées d'économies d'énergie grâce au transport, à l'assemblage, à la fabrication sans déchets, etc.

- Du besoin de travaux supplémentaires à réaliser pour éviter une compréhension subjective et une prise en compte déséquilibrée des trois dimensions de la performance durable, indépendamment de la portée et de la priorité des industries ou des fabricants.

Sur la base des conclusions et des recommandations, les perspectives suivantes sont pertinentes à prendre en compte pour une étude future. Des évolutions peuvent être apportées à la fois sur la méthode et sur l'approche globale pour prendre en compte la performance durable de la fabrication. Concernant la méthode, trois aspects peuvent être enrichis dans la continuité des travaux.

Le premier concerne la mise à jour et l'enrichissement de tous les SPI. Ce point sera traité par la suite.

Le deuxième concerne le processus de décision. L'étude montre qu'un processus de décision basé sur autant de critères reste particulièrement complexe et fragile. Il est nécessaire de faire évoluer l'approche pour améliorer sa robustesse. Ce constat illustre également le fait que la performance durable n'est pas toujours considérée de la même manière. Selon le point de vue, les attentes sont différentes en matière d'environnement, par exemple.

Le troisième point concerne la précision et la pertinence des modèles associés aux indicateurs de performance. En effet, les données disponibles au moment de la prise de décision restent assez imprécises. Le modèle de décision doit donc être enrichi pour en tenir compte. Ainsi, l'amélioration des méthodes de prise de décision pourrait être rendue possible par des données appropriées associées à chaque indicateur de performance durable. Ces données peuvent être intégrées dans de nouvelles études sur les nouveaux matériaux et les nouvelles méthodologies pour une meilleure évaluation de la performance durable grâce à de nouvelles méthodes analytiques pour le contrôle des processus et l'optimisation des paramètres.

En ce qui concerne l'approche globale, il semble que le problème clé concerne l'expression de toutes les indicateurs de performance. L'établissement d'une liste pertinente est un problème complexe car proposer une liste exhaustive tend à en augmenter la taille. En outre, cette liste dépend beaucoup de l'évaluation par l'entreprise elle-même de l'impact environnemental et social du processus de fabrication. Cette évaluation évolue nécessairement dans le temps, en fonction des développements technologiques. Ainsi, plusieurs points particuliers peuvent être évalués.

L'intégration de la fabrication dans le processus global de fourniture de produits qui répondent aux besoins fonctionnels des clients implique qu'il faudra prendre en compte de nouveaux indicateurs liés aux interactions entre les processus depuis la définition du besoin jusqu'à la livraison au client. La question est de passer d'une fabrication durable à une satisfaction durable du client.

Cette étude a isolé un ensemble de 68 indicateurs, compte tenu de l'état actuel de la littérature. Cependant, les changements technologiques dans les processus de fabrication, les produits et, surtout, les attentes de la société peuvent faire évoluer cet ensemble d'indicateurs. En effet, nous pouvons constater que l'appréciation de la performance durable évolue dans la société. Les aspects environnementaux sont devenus plus importants. Il en sera de même pour les aspects sociétaux. Par conséquent, la révision régulière de tous les indicateurs est une nécessité.

La prise en compte de la performance durable dans les processus de conception et de fabrication interagit avec l'environnement social, par la prise en compte de normes pour la consommation des ressources, les émissions et l'impact humain et de guides pour le développement de nouveaux matériaux, processus et produits. De cette manière, les indicateurs sont directement liés aux changements de pratiques et de normes. De même, l'intégration de ces indicateurs dans les processus de décision en matière de fabrication peut également contribuer à susciter des changements dans les pratiques et les normes. Ainsi, l'impact de la fabrication dans l'évolution de la société est renforcé.

Ce travail permet d'exprimer la performance durable de la fabrication additive par rapport aux procédés plus conventionnels. Les limites sont donc identifiées. Il peut être pertinent d'utiliser cette méthode pour identifier les évolutions technologiques nécessaires à la fabrication additive afin de la rendre plus durable et donc plus compétitive. Actuellement, la fabrication additive est à la recherche de sauts technologiques lui permettant d'améliorer les finitions de surface, de réduire les activités de post-traitement, d'améliorer la vitesse et le volume de production, d'améliorer les propriétés mécaniques et de réduire l'impact de la poudre sur la santé humaine. Pour ce faire, il est nécessaire de rechercher des moyens qui prennent nécessairement en compte la performance durable pour l'améliorer.

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## List of Acronyms

3DP	3D Printing
3Rs	Reuse, Reduce and Recycle
6Rs	Reuse, Reduce, Recycle, Recover, Redesign and Remanufacture
ABS	Acrylonitrile Butadiene Styrene
AHP	Analytic Hierarchy Process
AM	Additive Manufacturing
AMOPSO	Adaptive Multi-Objective Particle Swarm Optimization
ASA	Acrylonitrile Styrene Acrylate
BDS	Biodiversity (impact management)
BPD	Blown Powder Deposition
BPT	Blown Powder Technology
CAD Model	Computer Aided Design model (or Computer Model)
CAD	Career Development
CATs	Computation of Adapted Tool Shape
CBR	Case-Based Reasoning
CE	Concurrent Engineering
CI	Consistency Index
CM	Conventional Manufacturing
CNC	Computer Numerical Control
CO2PE	Cooperative Effort on Process Emissions in Manufacturing
CON	Conformity
COR	Corruption
CUS	Customer Satisfaction
CWE	Cutter Workpiece Engagement
DCM-PSS	Dynamic Cellular Manufacturing Product-Service System
DEA	Data Equipment Analysis
DfAM	Design for Additive Manufacturing
DfM	Design for Manufacturing
DfSM	Design for Sustainable Manufacturing
DFX	Design for X
EBM	Electron Beam Melting
EC	Economic dimension of sustainability
ECE	Economic value
ECO	Economic cost
EDU	Education
EEX	Expenditure
EFF	Efficiency (workers' performance)
EFI	Fines (associate to GHG emission)
EIA	Environmental Impact Assessment
ELECTRE	ELimination Et Choix Traduisant la REalité
EMD	Demographic Structure
EMJ	Job Creation
EMO	Employment performance



EMR	Job retention rate
EMS	Job Security
EMT	Employment Type
EN	Environment dimension of sustainability
ENC	Energy consumption
ENE	Energy efficiency
ENR	Renewable Energy
EPA	United States Environmental Protection Agency
EQF	Equity and fairness (equal right and freedom)
ESA	Sanctions (noncompliance to environmental regulations)
FBA	Financial benefit and assistance (government or other source)
FDM	Fused Deposition Modeling
FSG	Fitness Sharing Genetic Algorithm
FST	Fuzzy Set Theory
GHG	Greenhouse Gas emissions
GOP	Goal Programming
GTMA	Graph Theory and Matrix Approach
HAB	Habitat (restored or protected)
HDPE	High Density Polyethylene
HM	Hybrid Manufacturing
IMK	Indirect economic impacts such as job creation
INR	Injury incident (rate)
INV	Infrastructure investment and services for public benefit
IRD	Expenditures associated to innovation and R&D
ITR	Environmental impact of transporting products
LAN	Land (protected and areas of high biodiversity)
LBM	Laser Beam Melting
LCA	Life Cycle Assessment
LMD	Laser Metal Deposition
LOC	Local hiring or involvement of local community
MAA	Material availability
MAB	Marketing Benefits
MAC	Material consumption
MAE	Material efficiency
MAR	Material recycling
MAUT	Multi-Attribute Utility Theory
MAV	Value recovery
MCDA	Multicriteria Decision Analysis
MCDM	Multi Criteria Decision Making
MIND	Method for analysis of Industrial energy systems
NCI	Noncompliance Incidents (marketing benefits)
NCR	Noncompliance records
NLPP	Nonlinear Process Planning
OEMs	Original Equipment Manufacturers
PAP	Primary Air Pollutants

PBT	Powder Bed Technology
PC	Polycarbonate
PETG	Polyethylene Terephthalate Glycol
PIN	Product Information
PLA	Polylactic acid
PLC	Product Life Cycle
PMMA	Poly (Methyl Methacrylate)
POP	Policy and Procedures
PROMEETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PSI	Initiatives to mitigate environmental impacts
PSP	Packaging
PUT	Public Trust
RI	Random Index
RIS	Risk (impact on human health)
RMA	Renewable materials
SAP	Secondary Air Pollutants
SAW	Simple Additive Weighting
SDGs	Sustainable Development Goals
SEC	Specific Energy Consumption
SFI	Monetary values of fines for noncompliance with social laws and regulations
SGR	Grievances related to human rights
SKM	Skill Management
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Sustainable Manufacturing
SMART	Simple Multi-Attribute Rating Technique
SO	Social dimension of sustainability
SPAF	Sustainable Process Analytics Formalism
SPD	Sustainable Product Design
SPI	Spills (number and volume affecting ecosystem and human health)
SPIs	Sustainability Performance Indicators
SSA	Nonmonetary sanctions for noncompliance with social laws and regulations
STR	Strategy of transportation or logistics
SUP	Spending on locally based suppliers (policy, practice and proportion)
TBL	Triple Bottom Line
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TPU	Thermoplastic Polyurethane
TPU95	Thermoplastic Polyurethane
TRE	Training and Education
TRP	Transparency
UAM	Ultrasonic Additive Manufacturing
UMW	Ultrasonic Metal Welding
UNEP	United Nations Environmental Program

UNIDO	United Nations Industrial Development Organization
UPLCI	US Unit Process Life Cycle Inventories
US DoC	United States Department of Commerce
VAL	Monetary values of fines for noncompliance (PSS)
WAAM	Wire Arc Additive Manufacturing
WAC	Water consumption
WAD	Water discharge
WAG	Standard entry level wages
WAI	Water impact
WAR	Water recycled
WAS	Waste
WDT	Wire Deposition Techniques
WFR	Workforce representation

## Declaration of Authorship

I, Getasew Ashagrie TADDESE, declare that the contents of this Ph.D. dissertation are my own and have been generated by me as the result of my original research entitled “*Multicriteria decision-making methodology for sustainability evaluation in the design and manufacturing of engineering products - Application to Additive Manufacturing.*” I confirm that this work was done wholly or mainly while in candidature for a research degree at this University, where I have consulted the published work of others, this is always clearly attributed, part of this work have been submitted for publication to the journal of advanced manufacturing technology entitled “*Sustainability performance indicators for additive manufacturing: A literature review based on product life cycle studies*” and is already published and another article entitled “*Application of Multicriteria Decision Making Methodology for sustainability evaluation of Faceshield bracket manufacturing*” is ready for publication.

Signature: .....

Date: .....

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Ph.D. dissertation

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# Chapter 1

## Background and Justification of the Study

### 1.1 Introduction

Sustainability evaluation of the design and manufacturing of engineering products plays a significant role to improve the overall quality of life in the current socio-economic systems. Unfortunately, several studies reveal that manufacturing activities represent a significant burden on the environment (Haapala et al., 2013), which is an important dimension of sustainability. In manufacturing system advancement, according to (Zhang et al., 2013), the three important considerations are mass production, globalization and increased demand for sustainable products, ecological concerns, and social responsibility policies (Zhang et al., 2013). Thus, it is highly demanded that the focus of the manufacturing system must be balancing economic, environmental, and social objectives rather than focusing only on economic benefits, which in other words means that it is the time to view manufacturing system advancement for sustainable manufacturing.

According to the U.S. Department of Commerce (DoC), sustainable manufacturing is defined as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound” (Shao et al., 2017). A similar approach has been given to sustainable product design on a review by (Ahmad et al., 2018) on their recent revision of tools, applications, and research perspectives on sustainable product design and manufacturing. A similar definition of sustainable manufacturing is given by the U.S. Environmental Protection Agency (EPA) as “the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources.”

Moreover, various recent studies reveal that sustainable manufacturing is being taken as an effective solution to support the continuous growth and expansion of manufacturing engineering as a strategy for reducing the environmental impact and improving the economic performance of the manufacturing industry. According to (Haapala et al., 2013; Yuan et al., 2012), sustainability focuses not only on analyzing the environmental performance of manufacturing processes and systems but also on socioeconomic system considerations. But according to (Haapala et al., 2013) environmental impacts specific to products are largely determined during the design stage. It also has a significant impact on companies' business performance and competitiveness (Shao et al., 2017).

Environmentally sustainable manufacturing systems have traditionally focused either on the design of environmentally conscious production systems or the design of closed-loop supply

chains that consider the life cycle of a product from cradle to gate (Haapala et al., 2013). But several kinds of research tried to express sustainable manufacturing as a complex system that can be affected by various factors of economic, environmental, and social issues. Changes in the system dynamics usually result in dynamic changes in these factors. Besides, manufacturing industries are challenged by economic and financial priorities against environmental and social priorities (Zhang et al., 2013). Thus, in the design of sustainable manufacturing systems, concurrent and balanced consideration of these factors must be considered, which needs proper multicriteria decision-making approaches and/or methods.

Intending to assess companies' manufacturing operations, a study by (Joung et al., 2013) presented reviews of publicly available indicator sets and provides a categorization of indicators related to manufacturing. In this study, the indicator categorization structure considers the main sustainability dimensions (environment, economic and social) but separately treated additional dimensions as technological advancement and performance management could have been included within one of the main categories. Moreover, as per recent reviews and as compared to commonly available indicator sets and guidelines, more sustainability performance indicators could have been added to make the indicator sets more comprehensive for better sustainability evaluation in the manufacturing of engineering products.

In sustainable manufacturing evaluation, some different approaches and methods have been used for sustainable manufacturing evaluation but these approaches and methods are developed depending on the limited scope and incomplete coverage of each dimension. The following list show selected approaches and methods.

1. Sustainable manufacturing system thinking - A study by (Zhang et al., 2013) consideration of a combined approach of the principle of sustainable manufacturing system thinking in the form of system dynamics to develop a conceptual model. It supports an understanding of the complex interaction factors within the defined system. Complex problems will be understood as systems of an interconnected set of problems. Furthermore, system thinking provides a framework to holistically analyze and understand system behaviors.
2. Sustainable manufacturing through technological improvement - According to (Yuan et al., 2012), for sustainable manufacturing through technological improvement, process-based analytical models play an important role in quantifying the inputs (material, energy, etc.) and outputs (products, emissions, and waste). Material flow analysis and energy flow analysis are the two widely adopted tools to quantify and track the material/energy flows in manufacturing.

3. The framework of design for sustainable manufacturing - A framework of design for sustainable manufacturing (DfSM) was developed by Garbie, which aggregates international and contemporary issues, innovative products, reconfigurable manufacturing systems, manufacturing strategies, performance measurements, and flexible organizational management into a single index using a weighted sum approach (Haapala et al., 2013).
4. Sustainable assessment methodology - A sustainable assessment methodology is developed by (Eastwood and Haapala, 2015) to both improve the accuracy of existing approaches in identifying the sustainability impacts of a product and to assist manufacturing decision-makers. Methodology developed utilizes unit process modeling and life cycle inventory techniques. Moreover, a study by (Shao et al., 2017) introduced a systematic decision-guidance methodology that uses sustainable process analytics formalism (SPAF) developed at the National Institute of Research and Technology. The methodology provides step-by-step guidance for users to perform sustainability performance analysis using SPAF which supports data querying, what-if-analysis, and decision optimization for sustainable metrics.

To sum up, though various efforts are being made by various researchers, there exists a huge gap in understanding the term sustainability, concurrent and balanced consideration of sustainability dimensions as well as consideration of performance indicators for each dimension and sustainability evaluation approaches and methodologies. Moreover, the shift to design for additive manufacturing brought better opportunities for sustainability performances of additive manufacturing over conventional manufacturing which needs further analysis.

Thus this study addresses the gap on the comprehensive list of sustainability performance indicators which can be compared to standards for the selected application, analysis of sustainability performance of additive manufacturing, and finally propose a multicriteria decision-making methodology which can compare multiple, conflicting criteria to prioritize based on the intended goal.

## **1.2 Background of the study**

The background of this study is organized into four sections. The first section focuses on industries' and manufacturers' needs assessment to fulfill requirements of sustainable manufacturing and also existing practices of enhancing sustainability. The second section explains opportunities of shifts towards design for additive manufacturing (DfAM) for sustainability performance which directs evaluation of sustainability performance of additive manufacturing and how opportunities in minimizing manufacturing constraints and enhanced design flexibilities assist in enhancing better sustainability. The third section focuses on identifying gaps in the existing sustainability performance indicators which is used as background to propose a better, comprehensive list of sustainability performance indicators. The last and



fourth section assesses the need for sustainability evaluation methodologies which can be used as a motive for the development of decision-making methodology for sustainability evaluation.

### **1.2.1 Sustainability in manufacturing industries**

Various industries are currently being advised and guided by the outcomes of scientific researches either from their research and development department (R&D) team and/or from the wider pool of the scientific community. Moreover, the 2030 sustainable development goals by the United Nations industrial development organization (UNIDO) made several actions as part of the SDGs. Part of the actions is addressed by evaluating the sustainability of manufacturing processes and product sustainability evaluation throughout its life cycle. So far, there are various approaches recommended to industries by several researchers on which approaches to follow for their demand of sustainable manufacturing. They must make informed decisions in considering simultaneous but balanced consideration of economic, environmental, and social aspects in design, product development, and process flow (Eastwood and Haapala, 2015). Besides, more researches are focusing on increasing energy efficiencies towards reducing costs and environmental burden to alleviate industries challenge in balancing economic and financial priorities against environmental and social responsibilities (Zhang et al., 2013), (Ahmad et al., 2018).

Therefore, many industries and original equipment manufacturers (OEMs) are employing practices to make their operation and manufacturing process more sustainable by increasing energy efficiency (Shao et al., 2017). The industrial sector uses more energy than other end-use sectors, consuming about half of the world's total energy. As reported in (Shao et al., 2017) by citing a manufacturing energy consumption survey between 2010 and 2013 and environmental impact assessment (EIA) reports, both manufacturing energy use and energy-intensive manufacturing activities have been reduced because of the manufacturer's effort. Some manufacturer's also used energy management systems. So far, the common practices of sustainable manufacturing focused more on energy issues but less coverage on complete coverage of the three dimensions. Therefore, there is a need for further study on sustainability consideration in manufacturing industries.

### **1.2.2 Shifts towards DfAM and opportunities for sustainability**

Manufacturing constraints are key challenges in product design and development. Design considerations and integration of all aspects of sustainability in the existing CM processes were challenged by manufacturing and associated constraints and had limitations to fully address all the three dimensions of sustainability called the TBL perspective (Borchardt et al., 2011; Bovea and Pérez-Belis, 2012; Jin et al., 2017; Peralta Álvarez et al., 2017) which can be achieved by systematically considering the tradeoffs among possible PIs.

However, based on recent developments, there is a highly emerging shift from design for manufacturing (DfM) to design for additive manufacturing (DfAM) which will enable design for minimized manufacturing constraints. This will give better opportunities to design intricate shapes of engineering products with better sustainability performance. Furthermore, life cycle aspects of products are recently becoming major concerns of many industries, OEMs, and researchers on the subject. Though the definition of sustainability and sustainable manufacturing itself varies, (Haapala et al., 2013; Yuan et al., 2012) provided a more meaningful definition of sustainability as “analyzing both the environmental performance and the socioeconomic system considerations of manufacturing processes and systems”. It can focus on either design of environmentally conscious production systems or the design of closed-loop supply chains that consider the life cycle of a product from cradle to gate. Thus, opportunities of DfAM can be exploited to fully accommodate or give a more meaningful definition of sustainability.

To capture the possible opportunities of DfAM, it is necessary to identify and understand the sustainability performance of additive manufacturing (AM) as compared to conventional manufacturing (CM) processes. AM enables the design and production of multi-material, multifunctional, monolithic, and customized parts of products that will be evaluated for sustainability associated with environmental, economic, and societal impact. Moreover, it allows direct printing from CAD model, optimization, prototype manufacturing, flexibility, complexity, product customization, resource efficiency through the realization of an optimized object, operation-related issues, supply chain (Gardan and Schneider, 2015; Gebisa and Lemu, 2017; Huang et al., 2013; Jared et al., 2017; Nathan, 2015; Sossou et al., 2018; Tang et al., 2016; Thompson et al., 2016).

Besides the advantages mentioned, it is also necessary to be aware of the common limitations. These include high cost of machine and material as an initial investment, poor surface finish (cause for extended post-processing activities), less production volume and building speed (the reason for low productivity), dimensional stability, uncertainty in final part mechanical properties, the impact of powder on human health, etc. The post-processing activities are used to improve the microstructure, reduce porosity and to finish surfaces, reduce roughness and meet geometric tolerance. (Bikas et al., 2016; Bourell et al., 2017; Frazier, 2014; Giffi et al., 2014; Gupta et al., 2012; Hapuwatte et al., 2016; Huang et al., 2013; Sossou et al., 2018; Vaneker, 2017; Yang and Zhao, 2015).

Research efforts into the design for additive manufacturing (DfAM) have been mostly dedicated to part's design, which is a requirement for a better industrial adoption (Sossou et al., 2018). Since AM is capable of manufacturing fully functional assemblies requiring a few or no assembly operations, there is a need for DfAM methodologies tackling product developments more holistically, and which are, therefore dedicated to assembly design.

### **1.2.3 Gaps in existing sustainability performance indicators**

Assessing existing sustainability evaluation metrics or performance indicators was necessary to understand how sustainability has been presumed by several researchers in academia. The gap observed in this regard was not only just the omission of a balanced consideration of the three dimensions but also incomplete, inconsistent, and lack of a comprehensive list of *sustainable performance indicators* (SPIs) for each dimension. A study by (Reich-Weiser et al., 2008) tried to develop SPIs focused on energy use, climate change, and nonrenewable resource consumption. But social dimension is entirely missing, and there are still unconsidered yet vital sustainability indicators that fully characterize sustainable manufacturing.

Through several efforts of quantifying sustainable performance, there is an incomplete and subjective consideration of SPIs which did not convince many researchers and engage themselves in developing simple, complete, and high-level SPIs which can be compared with standards for various applications (Ahmad et al., 2018; Cohen et al., 2014; Rachuri et al., 2011). Furthermore, (Ahmad et al., 2018), suggests that more case studies, overlooking the design stages and utilization of more data and metrics, are still required to fully assure sustainability as most of the previous studies tried to assure sustainability by limiting its scope to economic or environmental dimensions based on subjective interests.

Because most of the SPIs currently identified are more focused on evaluating environmental performance (Ahmad et al., 2018; Buchert et al., 2014; Rossi et al., 2016; Yuan et al., 2012) than considering complete sustainability indicators (Jain, 2005), and also as per many of the sustainability guidelines cited by authors such as (GRI, 2000), it is important to have a comprehensive understanding and balanced consideration of all PIs for measuring all dimensions throughout the life cycle of the product (Ahmad et al., 2018; Eastwood and Haapala, 2015; Haapala et al., 2013; Joung et al., 2013; Shao et al., 2017; Yuan et al., 2012).

### **1.2.4 Need for sustainability evaluation methodologies**

Once a complete list of indicators are developed based on the three dimensions of sustainability, it is necessary to develop a comprehensive decision support models that did not lack interoperability for total life cycle sustainability assessment that consider innovations at a product, process, and system levels which can allow evaluation of sustainability from all dimensions (Badurdeen and Jawahir, 2017).

Except for the LCA guidelines for product-based assessment by UNEP and despite several efforts, to date, there is no commonly accepted method to adopt social impact assessment of manufacturing systems. Besides, Engineering research failed to provide appropriate tools to assist decision on manufacturing system which is now focusing on balancing the three dimensions of

sustainability (economic, environmental, and social responsibilities) rather than focusing only on economic benefits since sustainable manufacturing strictly requires simultaneous and balanced consideration of environment, economic and social implications throughout the products' life cycle (Zhang et al., 2013), (Ahmad et al., 2018; Haapala et al., 2013).

A high level of sustainability will be achieved through the development of new comprehensive multicriteria methodologies which can formally describe, analyze, evaluate, and optimize sustainability performance metrics for manufacturing processes and systems (Shao et al., 2017). Designers wishing to promote sustainable manufacturing must weigh factors such as time, quality, resources, and costs along with environmental performance. Conflicts between environmental, economic, and social factors are highly probable and require the application and development of multicriteria decision-making (MCDM) (Haapala et al., 2013). So far, several methodologies have been used associated with sustainability and sustainable manufacturing. According to (Zhang et al., 2013), researchers have applied system dynamics to solve sustainability-related problems for several decades but studies are limited in modeling sustainable systems.

Therefore, one can understand that further work is needed in understanding and addressing sustainability in manufacturing industries, issues of sustainability and sustainability performance indicators, and the need for new multicriteria decision-making methodologies. Thus, this study is intended to focus on analyzing the sustainability performance of additive manufacturing processes, a proposal of a comprehensive list of sustainability performance indicators and developing a multicriteria decision-making methodology based on the proposed indicators, where there is a noticeable gap.

### **1.3 Motivation to this study**

The current socio-economic systems expect an improved quality of life and manufacturing system advancement through mass production, globalization, and increased demand for sustainable products, ecological concerns, and social responsibility policies. This means a balanced and concurrent evaluation of the environmental, economic, and social dimensions of sustainability is highly essential. Studies show that product designers and manufacturers are not fully integrating these sustainability dimensions to the fullest.

Improving products' overall 'sustainability' performance was mostly related to the business (economic) aspect and less consideration has been made for human (environment and social) priorities. Moreover, the sustainability performance of a product was not often considered at its pre-design and design stage where the sustainability performance variations due to selection, processing, transportation, and stocking of raw materials and finished products as well as knowing the ease of manufacturability at an early stage was not given priority.

Thus, the fundamental motivations in this study are based on the desire to;

- Clarify understandings and definitions of sustainability
- Identify what is needed to evaluate the sustainability performance of manufacturing a product: from a manufacturing process perspective,
- Identify, analyze sustainability performances of additive manufacturing processes, assess existing sustainability performance indicators, and finally
- Identify, choose and propose a general approach of multicriteria decision-making methodology for sustainability evaluation.

#### **1.4 Statement of the problem**

More recently, sustainable manufacturing is being taken as an effective solution to support the continuous growth and expansion of manufacturing engineering as a strategy for reducing the environmental impact and improving the socio-economic performance of the manufacturing industry. Besides, sustainability should be understood more than analyzing the environmental performance of manufacturing processes and systems and must consider the socio-economic system. Moreover, according to (Haapala et al., 2013) product, specific environmental impacts are largely determined during the design stage. Also, sustainable manufacturing has a significant impact on companies' business performance and competitiveness (Shao et al., 2017). However, it is very important to select an appropriate method of manufacturing, where better sustainability performance can be achieved through consideration of relevant indicators from all dimensions.

In most cases, the manufacturing industries are challenged by economic and financial priorities against environmental and social priorities (Zhang et al., 2013). Thus, it is high time to consider and make informed decisions in considering simultaneous and balanced consideration of economic, environmental, and social aspects in design, product development, and process flow (Eastwood and Haapala, 2015). Besides, more researches are focusing on increasing efficiencies towards reducing costs and environmental burden to alleviate industries' challenge for a balanced consideration of economic and financial priorities against environmental and social responsibilities (Zhang et al., 2013), (Ahmad et al., 2018). Furthermore, as introduced earlier, many companies are employing practices to make their operation and manufacturing process more sustainable by increasing energy efficiency (Shao et al., 2017)., which is one important aspect but far from evaluating the sustainability of industrial operations and processes.

However, though the current research in manufacturing involves significant efforts in developing metrics and tools for sustainability performance analysis, there is still a huge gap in developing an exhaustive list of sustainability performance indicators and evaluation methods due to the level of subjectivity. So far, a better review of sets of indicators to measure the sustainability of

manufactured products and manufacturing processes, categorization, and method of how to use these indicators is reported by (Joung et al., 2013). Sustainability is presented in five dimensions as environmental stewardship, economic growth, social well-being, technological advancement, and performance management but comparing it with existing indicator sets and guidelines, there is work to be done to create a complete list of sustainability performance indicators. Since the definition of sustainability is widely accepted based on the three dimensions of sustainability and since it is possible to incorporate the two additional categories of technological advancement and performance management into the main dimensions, categorization into five dimensions was not necessary and it may mislead widely accepted understandings of sustainability.

Another relevant lesson taken from this background analysis is assuring sustainability or targeting sustainable performance can strongly depend on the method and type of manufacturing process. This can be analyzed through evaluations on sustainability performances of additive manufacturing versus conventional manufacturing processes. It is known that identifying and minimizing manufacturing constraints is very important in the design and development of products. Thus, identifying opportunities for manufacturing methods such as additive manufacturing with the potentials of minimizing manufacturing constraints will be highly expedient for designers. It is necessary to find out the pros and cons of each process to use it as an input for industries and OEMs.

The design and manufacturing of engineering products are based on several conflicting criteria which require multicriteria decision-making (MCDM) methodology for sustainability. Thus, the development of an effective new methodology is highly recommended to formally describe, analyze, evaluate and optimize sustainability performance metrics for manufacturing processes and systems. According to (Ahmad et al., 2018; Zhang et al., 2013), engineering research failed to provide appropriate tools to assist decision on manufacturing system which is now focusing on balancing the three dimensions of sustainability (economic, environmental, and social responsibilities) rather than focusing only on economic benefits. Moreover, sustainable manufacturing requires simultaneous consideration of economic, environmental, and social implications associated with the production and delivery of goods (Haapala et al., 2013). Application and development of MCDM methodology are necessary to avoid possible conflicts between dimensions of sustainability.

New materials and technologies require new manufacturing processes (such as additive and digital manufacturing) and novel analytical methods for process controls and parameter optimization regarding cost, reliability, quality, product flexibility, energy consumption, and fossil carbon emissions. A systematic approach from concept development, product design and manufacturing to product delivery and service as well as in forward and reverse supply chain



management is important for successful adoption of advanced manufacturing for sustainability (Jin et al., 2017).

New processes will transform manufacturing systems including, facility design, scheduling, process planning, material handling, workforce scheduling, quality control, and inventory management. To support the justification of how new technologies, in this case, Additive Manufacturing, it could help to quote the words of Dr. Rob Sharman, a global head of additive manufacturing at GKN Aerospace (Nathan, 2015). “Everything we currently make looks the way it does because of the way we make it, but nature doesn’t build anything the way we do,” said Sharman. “Now we finally have a process that can help us get closer to the way nature designs and builds things, but we are just at the start of it, and we have a long way to go to emulate that efficiency.”

Thus, it is very clear to understand that there are still challenges on this subject and some of these challenges, mentioned below, will be addressed through this study.

1. The subjectivity of definition or understanding of the term sustainability itself by researchers and industries. This subjectivity may lead to misunderstandings between researchers and industries on similar issues associated with sustainability.
2. Incomplete and inconsistent list of SPIs. Though there are various efforts from various researchers in proposing frameworks for indicators, comparing outcomes with more than 10 available indicator sets and guidelines, there still exists inconsistency, lack of balanced consideration, lack of update, incomplete description of indicators based on each sustainability dimension.
3. Evaluation based on comparative analysis of sustainability performance of additive manufacturing methods over conventional manufacturing methods. Identifying the advantages and disadvantages of each manufacturing process concerning sustainability performance is highly relevant. The analysis is mainly based on an intensive literature survey.
4. Lack of properly validated, comprehensive multicriteria decision-making framework for evaluating the sustainable performance of a product. During the last decade, various decision-making frameworks have been utilized by several researchers. But there was inconsistency, problem-specific, and lack of flexibility to use for different objectives or problems. Moreover, according to (Shao et al., 2017), those efforts that several manufacturing industries tried to implement sustainable manufacturing using methods that are customized, not reusable, and not extensible. Thus, a comprehensive MCDM methodology will be

proposed. The proposed methodology will be validated for functionality and effectiveness by applying it for the manufacturing of an engineering product.

To effectively address the problems mentioned above, the following research questions have been raised and addressed during the study.

1. What kind of subjectivity occur in understanding sustainability?
2. What are the most relevant sustainability performance indicators in the design and manufacturing of engineering products?
3. Which one is more efficient? Producing sustainable products or sustainability of manufacturing?
4. What relevant parameters needed for evaluating the sustainable performance of additive manufacturing?
5. How can one develop metrics and/or tools to improve the overall sustainability of manufacturing?
6. How to evaluate sustainability performances of additive manufacturing vs conventional manufacturing? Is assuring sustainability product/part dependent?
7. How can one develop a framework for total lifecycle-based material flow with holistic consideration of product, process, and system?
8. What can be done to assist decision-makers on either product or process design to assure sustainability throughout the life cycle of the product?
9. Which of the existing decision-making methods are more powerful/preferable for multicriteria decision-making? Why?

## **1.5 Objectives of the study**

### **1.5.1 General objective**

The general objective of this study is to develop a comprehensive multicriteria decision-making methodology for sustainability in the design and manufacturing of engineering products by considering additive manufacturing technology as one comparative manufacturing method.



### **1.5.2 Specific objectives**

The three main specific objectives are;

1. Development of a comprehensive list of sustainability performance indicators which can be compared to standards through intensive literature survey and comparison with existing indicator sets and guidelines.
2. Analyzing sustainability performance of additive manufacturing through comparative evaluation to conventional manufacturing processes based on existing works of literature by focusing on criteria selection schemes, design modification requirements and parameter selection approaches.
3. Development of a multicriteria decision-making methodology for sustainability evaluation by using Analytic Hierarchy Process. This is considered a general solution that can be used as a reference for the design and manufacturing of engineering products. A case of Faceshield bracket manufacturing is taken as an application for validation and assessing the relevance of the proposed methodology.

### **1.6 Significance of the study**

As major significances of this study, the first part focuses on identifying, categorizing, and properly compiling a comprehensive list of sustainability performance indicators based on product life cycle studies. As per the wider pool of literature assessed, there is a need for further work on avoiding the existing level of subjectivity in consideration of performance indicators and the development of simple and high-level performance indicators which can be compared to standards. Utilization of more data and metrics is still required to fully assure sustainability as most of the previous studies tried to assure sustainability by limiting its scope to economic or environmental dimensions based on the interests of companies or stakeholders. This stage will help assist designers, manufacturers, decision-makers, and users to easily choose alternatives to model their problems to achieve their objective while a complete and balanced aspect of sustainability is considered.

The second part of the study is focused on analyzing the sustainable performance of additive manufacturing. This has been mainly done through an intensive literature review where advantages, disadvantages, and related relevances of additive manufacturing over conventional manufacturing methods are identified where this input is utilized for comparative evaluation of additive manufacturing for its sustainability performance. To achieve this, a comparative analysis on the sustainability performance of additive manufacturing processes is done mainly

through an extensive literature survey by focusing on criteria selection schemes, design modification requirements, and approaches of parameter selection.

The third and last part of this study focused on the development of a comprehensive multicriteria decision-making methodology by using the Analytic Hierarchy Process (AHP) which takes into account the sustainability design activities and optimization of production processes where a case of Faceshield bracket is taken as an application for validation for relevance and effectiveness of the proposed methodology.

### **1.7 Scope of the study**

The scope of this study goes until the proposal of a multicriteria decision-making methodology using a Multicriterial decision-making methodology called AHP to evaluate the sustainable performance of different manufacturing processes. This methodology proposal is based on the newly proposed sustainability performance framework and indicators as part of this study where identification, categorization, and enrichment as well as validation for exhaustiveness is done. Moreover, the sustainability performance of additive manufacturing processes is analyzed as compared to conventional manufacturing processes. Finally, a case of Faceshield bracket manufacturing where identification of necessary parameters and sustainability performance analysis of manufacturing processes utilized is done as an application.

### **1.8 Organization of the study**

The study is organized into seven chapters. The first chapter focuses on the background and justification of the study which gives the general context of the whole work. The second chapter focuses literature review on key concepts needed for the scope of the intended study such as sustainability, sustainable manufacturing, design and manufacturing trends, and decision-making methodologies. The third chapter clarifies the research design and methodology followed to accomplish the intended objectives. Chapters four, five and six, are the main chapters to report major contributions of the study based on the three key specific objectives. These chapters report comparative evaluation results about the sustainability performance of additive manufacturing, the proposed framework of sustainability performance indicators, and developed MCDM methodology for sustainability evaluation of product manufacturing where a case of Faceshield bracket is used as an application respectively. Finally, conclusions, recommendations are future perspectives are reported in chapter seven.

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## Chapter 2

### Literature Review

An intensive literature search and review has been done by focusing on key relevant concepts such as sustainability, sustainable manufacturing, current trends in design and manufacturing, and decision-making methodologies focusing on a multicriteria decision making of analytic hierarchy process. The main goal of this chapter is to evaluate existing achievements of the scientific community and existing contributions on these areas which can be used as an input for problems, identified objectives set for this study. Even though most of the literature citations have been done for the past decade, some older scientific articles are also cited whenever relevant.

This chapter begins with a section presenting review outcomes on sustainability which mainly focuses on the subjective understanding of the term itself, understanding sustainability dimensions, and associated performance indicators. The second section focuses on analyzing the sustainability performance of manufacturing processes, which assesses categorizations in manufacturing processes and a more detailed discussion on conventional and additive manufacturing processes. The third section focuses on current trends of design and manufacturing and the fourth section focuses on decision-making methodologies where AHP is discussed in detail and methodologies and approaches relevant for sustainability evaluation of manufacturing processes are also assessed. Finally, a summary and implications from the literature review and gaps observed are reported.

#### 2.1 Sustainability

A more comprehensive definition of sustainability is proposed by (Haapala et al., 2013; Yuan et al., 2012), as it is analyzing both the environmental performance and the socioeconomic system considerations of manufacturing processes and systems. It can focus either on the design of environmentally conscious production systems or on the design of closed-loop supply chains that consider the life cycle of a product from cradle to gate.

##### 2.1.1 Subjective understandings of sustainability

One of the subjective understandings of sustainability is defining it with ecodesign. At first glance, ecodesign is scope within sustainability, but can't be used to completely address sustainability issues. Though not a complete measure for sustainability, it is worth understanding ecodesign itself. In some studies, sustainability had been explained through ecodesign itself, though the explanation doesn't fully consider all dimensions of sustainability. According to (Rio et al., 2011), *ecodesign is understood as integrating environmental concerns into the design criteria of products or services to reduce significantly their negative impact, which is characterized by life cycle thinking. The product development phase is a collaborative process*

that involves the design, marketing, and manufacturing units of an industry for the succession of clarification requirements, conceptual design, embodiment design, and detail design. Furthermore, the following key understandings have been assessed and supplemented to better understand ecodesign.

1. The first understanding considered is one given by (G.EN.ESI Education Centre, n.d.; Rio et al., 2011), that defines ecodesign as the integration of environmental aspects into product design and development, intending to reduce adverse environmental impacts throughout a product's life cycle.
2. The second understanding by (Van Hemel and Cramer, 2002), which says eco-design aims to combine business-oriented design goals and environmental considerations to reduce environmental loads and increase eco-efficiency. It is related to creating eco-products or green products to strengthen companies' brand name, positive market appreciation, customer satisfaction, improved corporate image, reduced liability risks, improved business continuity, reduction of direct operational cost, better health, safety, and ethical values.
3. The third understanding by (Karlsson and Luttrupp, 2006) presents ecodesign as the concept that considers human priorities together with business interrelation for an improved product, method, and system development to reduce environmental impacts.

Thus, these understandings show that ecodesign can be a good approach to measure environmental performance than sustainability performance.

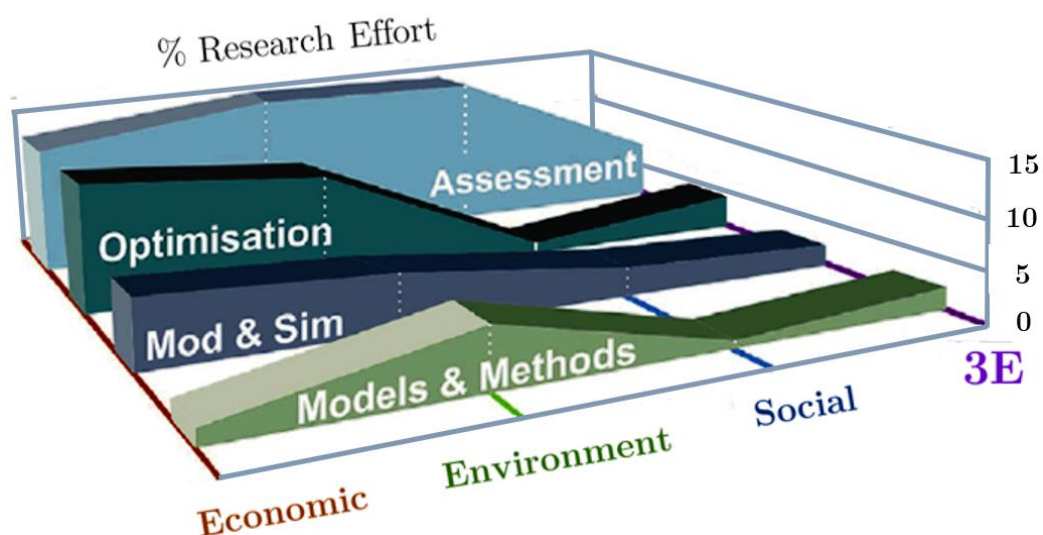


Figure 2.1 Characterization of research efforts (Peralta Álvarez et al., 2017)

However, the current challenge for conventional manufacturing industries (focusing on machining) to assure sustainability shows the fact that there is unequal coverage of the three dimensions in the four areas of design (models and methods), modeling and simulation, optimization, and assessment. Figure 2.1 reports efforts of characterization on recent researches as per the review by (Peralta Álvarez et al., 2017).

According to Figure 2.1, there is imbalanced consideration of the three dimensions where different stages in researches focused on one dimension without considering the effect on the remaining two. For example, the environmental dimensions were the centerpiece of current research and the social dimensions have been considered the least. Moreover, it can be seen that there was a growing research trend considering environmental and economic dimensions than social dimensions. One can easily observe that the environmental and economic dimensions are better distributed through four areas of design (models and methods), modeling and simulation, optimization, and assessment which showed less attention was given to the social dimension.

Most of the recent studies are highly recommending balancing economic and financial priorities against environmental and social priorities (concurrent consideration of these factors is advised) (Ahmad et al., 2018; Eastwood and Haapala, 2015; Shao et al., 2017; Zhang et al., 2013), which will be possible through manipulating opportunities of other advanced manufacturing processes such as additive manufacturing.

This concurrent consideration has benefits of increasing growth and global competitiveness, increase operational efficiency by reducing cost and waste, builds public trust, build long-term business liability and success and respond to regulatory constraints and opportunities (Moktadir et al., 2018).

The success of product development requires an integration of suppliers, process performance, project leadership, management system, customer involvement, effectiveness of product concept development (fit with market need and fit with firm competencies), market, financial performance but didn't boldly show consideration of environment as a key factor (Johansson, 2002).

According to a study by (Moldavska and Welo, 2017), different definitions given to sustainability led researchers and industries not to have a common understanding about it. Some understood sustainability as an environmental initiative, and some others as a goal or perspective. This has been disabling effective communication in the field of sustainable manufacturing between researchers and industry. Thus, here most widely available definitions and understandings of sustainability in design and manufacturing processes as reported by various researchers.



Sustainability is analyzing both the environmental performance and the socioeconomic system considerations of manufacturing processes and systems. It can focus either on the design of environmentally conscious production systems or on the design of closed-loop supply chains that considers the product life cycle from cradle to gate (Haapala et al., 2013; Yuan et al., 2012).

According (Ahmad et al., 2018), some studies show that definitions of sustainability are limited to scope to only economic and environmental dimensions without giving much attention to social dimensions. This is a similar observation that is presented by (Peralta Álvarez et al., 2017) shown in Figure 2.1.

Sustainable design and manufacturing is a creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound (Ahmad et al., 2018; Moktadir et al., 2018; Shao et al., 2017).

Sustainable manufacturing is favored on processes that utilize fewer and renewable materials that are not hazardous, modify production processes that use fewer materials and energy, use more efficient transport and logistics system, design products to be reusable, re-manufacturing, recyclable, and bio-degradable, and working with stakeholders and customers to reduce the environmental impact of the industry (Moktadir et al., 2018). Furthermore, in this study manufacturing is defined as one of the measures towards sustainable development by the UN as part of the SDGs.

### **2.1.2 Understandings on sustainability dimensions**

Since sustainability definition is entirely dependent on complete understanding and balanced consideration of sustainability dimensions, it is necessary to create a common understanding and how to use these dimensions for the intended purpose and the perspectives these dimensions are given. According to (Joung et al., 2013), sustainability dimensions are categorized into five as environmental stewardship, economic growth, social wellbeing, technological advancement, and performance management. As per the global understandings on sustainability, sustainability indicator categorization structure will be better understood by the wider scientific community when reported based on the three main sustainability dimensions; environment, economic and social.

The most meaningful sustainability framework based on the triple bottom line approach which is currently used is reported by (Peralta Álvarez et al., 2017) as shown in Figure 2.2. In this framework, the main dimensions are reported as environmental capital, economic capital, and human capital. It is shown that to produce products and services demanded by society, industries consume resources from nature, human resources as knowledge and release emissions and waste

and expose society to pollution. Thus, understanding the interconnections between these dimensions will help product manufacturers to understand and assure sustainability through efficient utilization of resources from nature and knowledge from society to produce products and services back to the society through minimized or no emission, waste, and exposure to pollution.

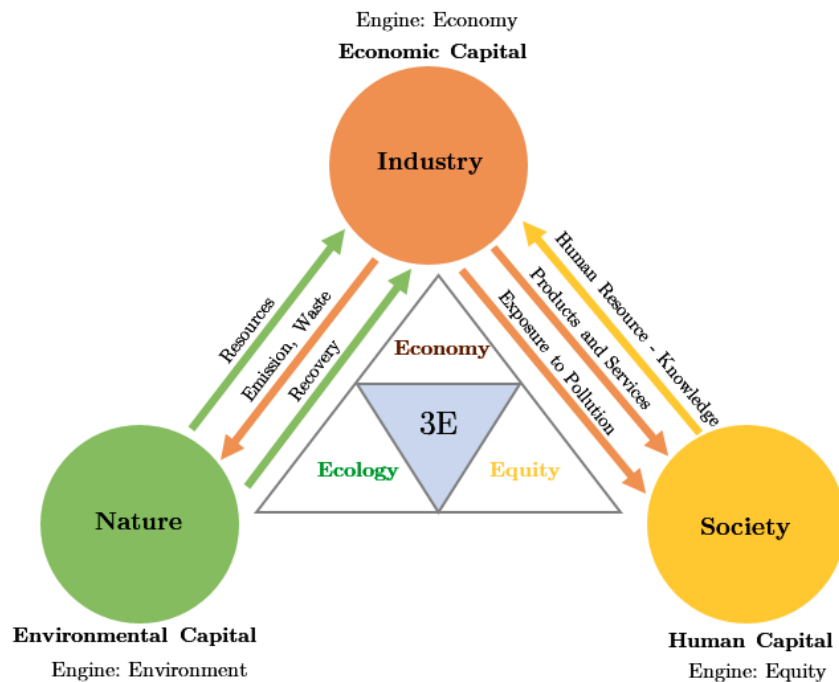


Figure 2.2 Current sustainability framework: Triple bottom line. (Peralta Álvarez et al., 2017)

In this section, the need for common understandings on sustainability dimensions is necessary because criteria for selection should not be subjective to the researcher or industry demand but look the impacts of the selected metrics to the three dimensions of sustainability such as the one by (Joung et al., 2013), where technological advancement and performance management are separately put as additional dimensions.

### 2.1.3 Sustainable Performance Indicators

Sustainability performance indicators (SPIs) are used in quantifying sustainable performances. But so far, there was incomplete and subjective consideration of sustainable performance indicators (SPIs) which still didn't convince various researchers and engage themselves in developing simple, complete, and high-level SPIs which can be quantified and compared to standards for various applications (Ahmad et al., 2018; Cohen et al., 2014; Rachuri et al., 2011). Furthermore, (Ahmad et al., 2018) suggests that more case studies, overlooking of the design stages and utilization of more data and metrics are still required to fully assure sustainability as most of the previous studies tried to assure sustainability by limiting its scope to economic or

environmental dimensions based on subjective interests. Thus, current research on sustainable manufacturing requires significant efforts on the development of SPIs and methodologies, tools, and approaches to evaluate and analyze sustainability performance.

So far, due to the lack of a holistic approach, engineers have tried to utilize different methodologies, from simple checklists to sophisticated analytical tools, to support product developments (Buchert et al., 2014). According to (Badurdeen and Jawahir, 2017) indicators can be used to develop comprehensive decision support models for total life cycle sustainability assessment that consider innovations at a product, process, and system levels which can allow evaluation of sustainability from all dimensions. Furthermore, better life cycle models enable more accurate prediction of costs and optimization of a product for maximized value products at lower costs throughout its life cycle. So far, there is no standard method for measuring the TBL achievement or comparison to enable a common scale and consistent evaluation of performance to provide measures of sustainability, reward, and incentives.

Thus, we consider that most of the SPIs currently identified are more focused on evaluating environmental performance (Ahmad et al., 2018; Buchert et al., 2014; Rossi et al., 2016; Yuan et al., 2012) than considering complete sustainability indicators (Jain, 2005). As per many of the sustainability guidelines cited by several authors, it is important to have a comprehensive understanding and balanced consideration of all SPIs. To measure all dimensions throughout the life cycle of the product (Ahmad et al., 2018; Eastwood and Haapala, 2015; Haapala et al., 2013; Joung et al., 2013; Shao et al., 2017; Yuan et al., 2012). Thus, further work is needed to exhaustively identify, quantify and generate a full list and description of SPIs. Proper categorization, as well as quantification of these indicators, is required to establish further decision-making frameworks or strategies in using additive manufacturing, as it gives better opportunities for designers and manufacturers towards achieving overall sustainability.

In the current sustainable manufacturing research, significant efforts are devoted to the development of metrics and tools for environmental performance analysis of manufacturing processes. But little work has been done in the system level of thinking for the development of an approach to improve the overall sustainability of manufacturing (Yuan et al., 2012).

Table 2.1 reports representatives of metrics (indicators) as per cited literature for reference including the purpose of knowing the indicator, measurement strategy, and possible ways of determining it in the product.

Table 2.1 Selected metrics for conventional and additive manufacturing

Resource usage (EN)	Reason	<ul style="list-style-type: none"> <li>• Energy (electricity, fuel, etc.)</li> <li>• Material (raw material, recycled material)</li> <li>• Water (for processing, for cooling, recycled water)</li> <li>• Land (occupied, affected)</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• Less net energy usage</li> <li>• Materials used vs material recycled</li> <li>• Used water vs recycled water.</li> <li>• Land restoration</li> <li>• Minimized energy/resource/material consumption</li> </ul>
	Possible ways of quantifying	<ul style="list-style-type: none"> <li>• D&amp; M</li> <li>• Proper material / process selection (D,M)</li> <li>• Using renewable materials. (D)</li> <li>• Resource efficiency (utilization of byproducts) (D).</li> <li>• Optimized product shape, size, and weight.</li> <li>• Design of lightweight products (AM) – results in less resource usage.</li> <li>• Increased material and energy efficiency through eco-design.</li> </ul> <p>Reduced energy consumption (material and product processing)</p>
	References	(Gupta et al., 2012; Hecht et al., 2012; Jin et al., 2017; Joung et al., 2013; Kulatunga et al., 2015; Salonitis and Ball, 2013)
Emissions, effluents, and waste (EN)	Reason	<ul style="list-style-type: none"> <li>• Atmospheric impacts (acidification, GHG, human health, ozone depletion)</li> <li>• Aquatic impacts (acidification, toxicity)</li> <li>• Impacts to land (hazardous and nonhazardous waste)</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• Minimized carbon emissions</li> <li>• Environmental friendly disposal where the product is biodegradable.</li> </ul>
	Possible ways of quantifying	<ul style="list-style-type: none"> <li>• D&amp; M</li> <li>• Minimized long-term environmental impacts and scoring a better environmental performance.</li> <li>• Environmentally sound products by considering global issues of global warming, climate change, ozone layer depletion, raising the sea level, soil, water, air pollution.</li> <li>• Minimized waste.</li> <li>• Designing manufacturing processes and products to have a lower environmental impact. Environmentally-conscious design and production.</li> </ul>
	References	(Cohen et al., 2014; Gupta et al., 2012; Hecht et al., 2012; Jin et al., 2017; Joung et al., 2013; Li and Mathiyazhagan, 2018; Tang et al., 2016)
Additional environmental items (EN)	Reason	<ul style="list-style-type: none"> <li>• Long term impacts (health, environmental)</li> <li>• Impacts of construction</li> <li>• Nature of penalties for non-compliance with regulations.</li> <li>• Utilization of renewable raw materials, long-term.</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• Minimized negative environmental and social impacts.</li> <li>• Compliance to regulations</li> <li>• Increased trends of using renewable resources.</li> </ul>
	Possible ways of quantifying	<ul style="list-style-type: none"> <li>• D&amp; M</li> <li>• Feasibility study</li> <li>• Design as per the national, regional, and international regulations related to the environment.</li> <li>• Trends of accommodating and utilizing raw materials from renewable energy sources.</li> </ul>

	References	(Hecht et al., 2012; Joung et al., 2013)
Profit, value, tax (EC)	Reason	<ul style="list-style-type: none"> <li>• Value of sales (V)</li> <li>• Cost of goods, raw materials, energy, services (C)</li> <li>• Tax</li> <li>• Gross margin = (V-C)</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• Less recurring manufacturing cost is profitable.</li> <li>• Global competitiveness</li> </ul>
	Possible ways of quantifying	<ul style="list-style-type: none"> <li>• D&amp; M</li> <li>• Minimized manufacturing cost.</li> <li>• Minimized repair/maintenance cost.</li> <li>• Profit gaining through proper marketing of product manufacturing.</li> <li>• Design products to be durable (reduced maintenance and improved lifetime costs)</li> <li>• Efficient processes make technology development less expensive to manufacture products. This can be achieved by replacing old technologies with new ones.</li> <li>• Process modifications that use environmentally safer materials, time-consuming, etc.</li> <li>• Packaging cost</li> <li>• Energy cost</li> <li>• Maintenance and repair</li> </ul>
	References	(Cohen et al., 2014; Giffi et al., 2014; Gupta et al., 2012; Hecht et al., 2012; Jayal et al., 2010; Jin et al., 2017; Joung et al., 2013; Kulatunga et al., 2015; Salonitis and Ball, 2013; Vaneker, 2017)
Investment (EC)	Reason	<ul style="list-style-type: none"> <li>• Capital (plant, associated infrastructure, stocks, working capital)</li> <li>• R&amp;D expenditure</li> <li>• Number of employees</li> <li>• Expenses (wages, benefits, training, etc.)</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• Devise mechanisms to build infrastructure at minimum cost.</li> <li>• Improve employees' efficiency.</li> <li>• Manufacture high-value products.</li> </ul>
	Possible ways of quantifying	<ul style="list-style-type: none"> <li>• D&amp; M</li> <li>• Labor cost</li> <li>• Recycling cost</li> </ul>
	References	(Hecht et al., 2012; Jayal et al., 2010; Joung et al., 2013)
Workplace (SO)	Reason	<ul style="list-style-type: none"> <li>• Employment situation (wage and benefit)</li> <li>• Health and safety (accident)</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• The attitude of companies towards treating their employees.</li> </ul>
	Possible ways of quantifying	<ul style="list-style-type: none"> <li>• D&amp; M</li> <li>• Ergonomics</li> <li>• Safer products</li> </ul>
	References	(Giffi et al., 2014; Hecht et al., 2012; Joung et al., 2013)
Society (SO)	Reason	<ul style="list-style-type: none"> <li>• An indirect benefit to society</li> <li>• Meetings with society</li> <li>• Complaints registered</li> <li>• Knowhow to society, free training, etc.</li> </ul>
	Measurement strategy	<ul style="list-style-type: none"> <li>• Enhance societal benefits</li> <li>• Minimize complaints</li> </ul>

Possible ways of quantifying	<ul style="list-style-type: none"> <li>• Meeting customer requirements and consumer preferences from new PD&amp;D.</li> <li>• Quality and safety aspects</li> <li>• Product detailing: it includes technical, quality and safety, environmental, economic, and legal aspects, and prototyping.</li> <li>• Avoid hazardous materials in the design and manufacturing process.</li> <li>• Reduced price</li> <li>• Reuse</li> <li>• Takeback options</li> </ul>
References	(Hecht et al., 2012; Joung et al., 2013; Kulatunga et al., 2015)

As shown in Table 2.1, metrics from each dimension of sustainability are mentioned regardless of the type of manufacturing process. The reason mentioned focuses on causes for need in this metrics, strategy of measurement depends on the objective or goal where optimum value (maximizing or minimizing depends on the goal) is needed as per the type of metrics. Moreover, possible ways of quantifying shows how one needs to consider these metrics at different stages of products' life cycle.

Machining has an impact on all three dimensions of sustainability. The energy consumption includes inline energy use, energy use for maintaining the working environment, energy use for material handling, etc. Moreover, the workers' safety is associated with exposure to chemicals, injury rate, near misses, and waste management is associated with the mass of consumables disposed of, reuse ratio of consumables, and recycled chip vs scrap ratio.

Energy efficiency is one of the key drivers of sustainability (Salonitis and Ball, 2013) which must be considered with other decision-making factors such as productivity, cost, flexibility. This literature reported an overview of the energy efficiency approaches for combined production and machine tool level (in an integrated manner). Most of the previous studies rely either solely on the monitoring of the energy consumption of machine tools or on the monitoring of specific machine tool components (e.g. spindle).

According to (Peralta Álvarez et al., 2017), there is an indication for a balanced consideration of sustainability dimensions:

1. Economic dimension: Chip, control parameters, coolant, cost, cutting conditions, fluid, information management, laws and standards, machine learning, material removal, energy and water resources, inputs, smart machining, quality surface, thermal energy, time, tool.
2. Environment dimension: Carbon footprint, ecological footprint, environmental impact, greenhouse gases, hydric footprint, impacts, inventory, material, raw material, resources, substance emission, toxicity, waste streams.

3. Social dimension: Accident, cognitive task, comfort/discomfort, ergonomics, and human factors, feedback machine (information task), human behavior, multi-response, risk, safety and health, semantic, skills (worker), special population, training, well-being, workplace, Kansei engineering<sup>1</sup>, and psychological feelings.

A study about strategies of value creation through sustainable manufacturing, (Badurdeen and Jawahir, 2017), proposed a vision for sustainable products, processes, and systems as shown in Figure 2.3.

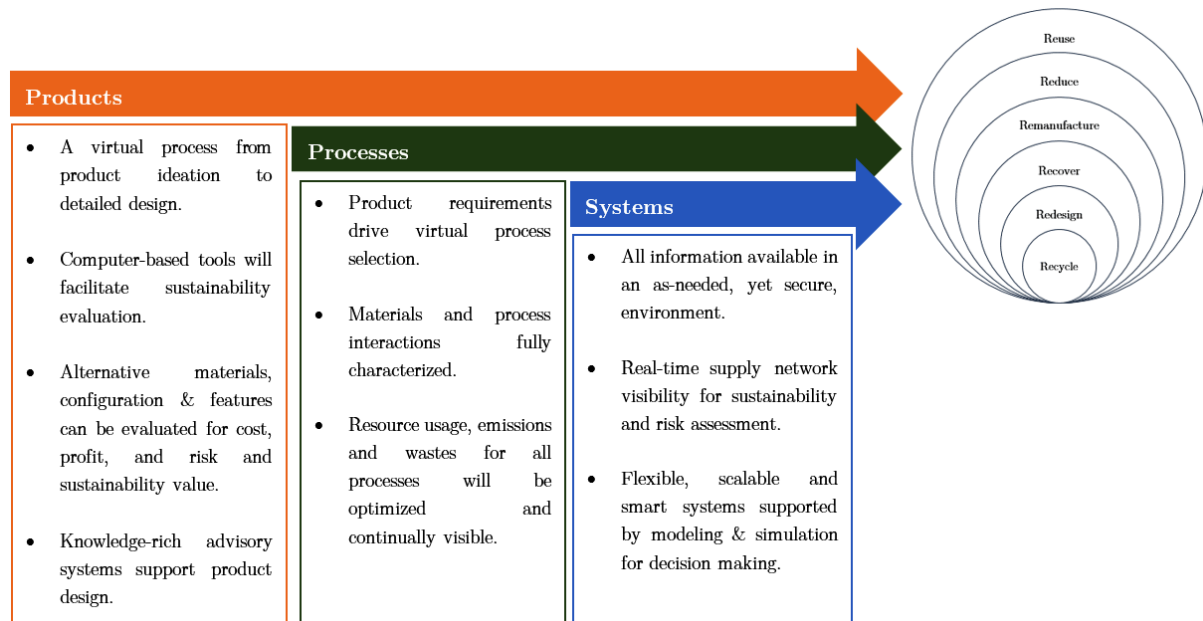


Figure 2.3 Visions for sustainable products, processes, and systems (Badurdeen and Jawahir, 2017)

Figure 2.3 reports illustration of sustainable value creation at the product, process, and systems levels to enable a closed-loop material flow-based approach to sustainable manufacturing. The system-based approach to design, manufacturing, and post-manufacturing activities.

## 2.2 Sustainability of manufacturing processes

Sustainable manufacturing (SM) is identified as one of the priority performance indicators by the US DOC (Shao et al., 2017) due to its capacities of both dimensions in improving quality of life and also minimize the burden on the environment by traditional Mechanical Manufacturing Systems (MMS). To reach sustainable manufacturing goals, (Haapala et al., 2013) recommends

<sup>1</sup> Kansei engineering (Japanese): emotional or affective engineering: aims at the development or improvement of products and services by translating the customer's psychological feelings and needs into the domain of product design (i.e. parameters).

that focus must be given to four categories: manufacturing process and equipment, manufacturing systems, changes in life cycle paradigms, and education.

Another more elaborated definition of sustainable manufacturing is given by (Moktadir et al., 2018) as utilization of renewable materials, use fewer materials and inputs that are not hazardous, modify production process that uses lesser materials and energy, use more efficient transport and logistics system, design products to be reusable, re-manufacturing, recyclable and bio-degradable and working with stakeholders and customers to reduce the environmental impact of the industry. Thus, to reach sustainable manufacturing goals, the focus must be given to four categories: manufacturing process and equipment, manufacturing systems, changes in life cycle paradigms, and education. Understanding and improving sustainability depends on understanding perspectives.

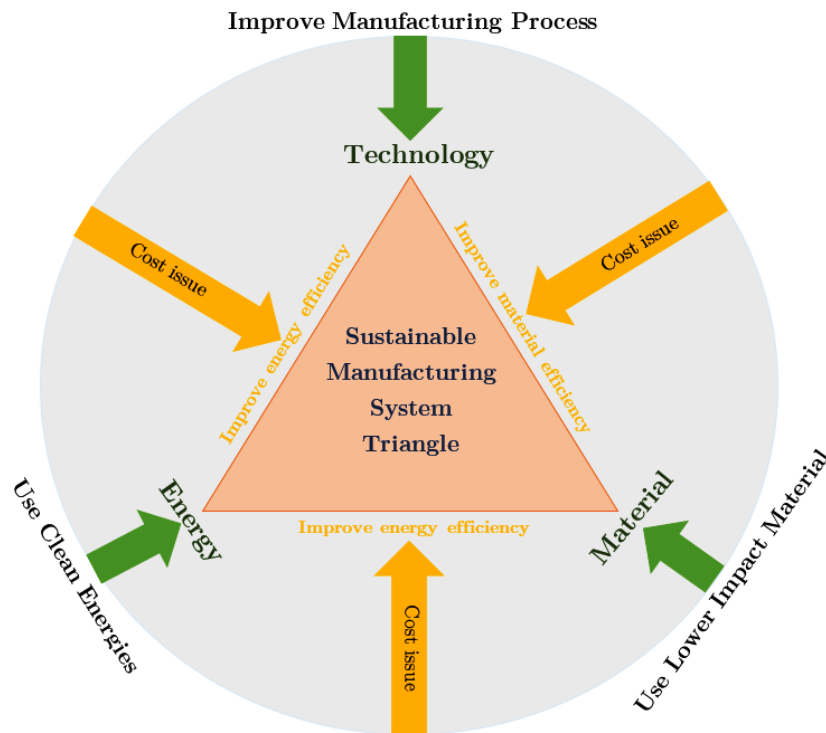


Figure 2.4 Sustainable Manufacturing system scheme (Yuan et al., 2012)

Figure 2.4 reports a system approach is developed to support industrial efforts in improving the overall sustainability of manufacturing from a pollution prevention perspective. The approach considers the three components of a manufacturing system: technology, energy, and material, a manufacturing system, and provides a framework for implementation of pollution prevention strategies to reduce the environmental impact and improve the sustainability performance of a manufacturing system.



According to a study by (Moldavska and Welo, 2017), manufacturing is defined as one of the measures towards sustainable development by the UN as part of the SDGs. Nevertheless similar to understandings on sustainability, there are different approaches or perspectives of defining sustainable manufacturing. Some of them are the following.

The US DOC defines sustainable manufacturing as the creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, consumers, and are economically sound through value recovery from end-of-life products (Badurdeen and Jawahir, 2017; Kulatunga et al., 2015; Li and Mathiyazhagan, 2018; Pigosso and McAloone, 2015; Shao et al., 2017).

A study by (Moktadir et al., 2018) describes sustainable manufacturing from two different approaches. The first approach is sustainability manufacturing, i.e., the process of creating manufactured products through economically-sound processes that minimize the total negative impact on the environment while conserving energy and resources. While the second approach is sustainable manufacturing, it uses renewable materials that don't deplete natural resources, use fewer materials and inputs that are not hazardous, modify production processes that use fewer materials and energy, uses more efficient transport and logistics systems, design products to be reusable, re-manufacturing, recyclable and bio-degradable and work with stakeholders and customers to reduce industries' environmental impact.

Lowell Center for Sustainable Production defines sustainable manufacturing as the creation of goods and services using processes and systems that are non-polluting, conserving of energy and natural resources, economically viable, safe and healthy for workers, communities, and consumers, socially and creatively rewarding for all working people (Gebisa and Lemu, 2017). The available tools for developing sustainable products or assessing the sustainability of products produced by conventional manufacturing systems can be extended to additive manufacturing.

### **2.2.1 Categorizing manufacturing processes**

In the study of sustainability, understanding the different types and requirements of manufacturing is highly relevant for decision-makers. This helps for better consideration of sustainability requirements at different stages of products' life cycle. In this study two major categories of manufacturing are considered, conventional and additive manufacturing, to assess requirements and considerations for better sustainability performance.

A study by (Badurdeen and Jawahir, 2017) categorized manufacturing processes into four types: traditional, lean, green, and sustainable manufacturing. The use and post-use issues of products' life cycle have been major issues for classification. For example, landfilling for traditional manufacturing, reduce for lean-manufacturing, 3Rs for green manufacturing, and 6Rs for

sustainable manufacturing. The 3Rs are Reuse, Reduce and Recycle and the 6Rs include Recover, Redesign, Remanufacture in addition to the 3Rs. Traditional product design focuses on product functionalities, quality, and cost of products to meet customer requirements whereas Sustainable Product Design (SPD), on the other hand systematically considers the entire product life cycle in terms of functionality, environment, and economic performance (Ahmad et al., 2018).

According to (Ahmad et al., 2018), sustainability expressed through the three aspects must be considered as an integral part of sustainable design which initially was focusing only on the environment as a concern for product design. For example, during the first wave of sustainability, it was developed as an environmental-friendly or ecological aspect (ecodesign). Moreover (Rossi et al., 2016) reported that most previous designs focus on developing tools such as eco-design or design for the environment giving more weight to it than considering the other two dimensions.

Implementing sustainable manufacturing using 6R enables closed-loop, total life cycle based material flow (pre-manufacturing, manufacturing, use, post-use), with a holistic consideration of a product, process and system levels (Badurdeen and Jawahir, 2017).

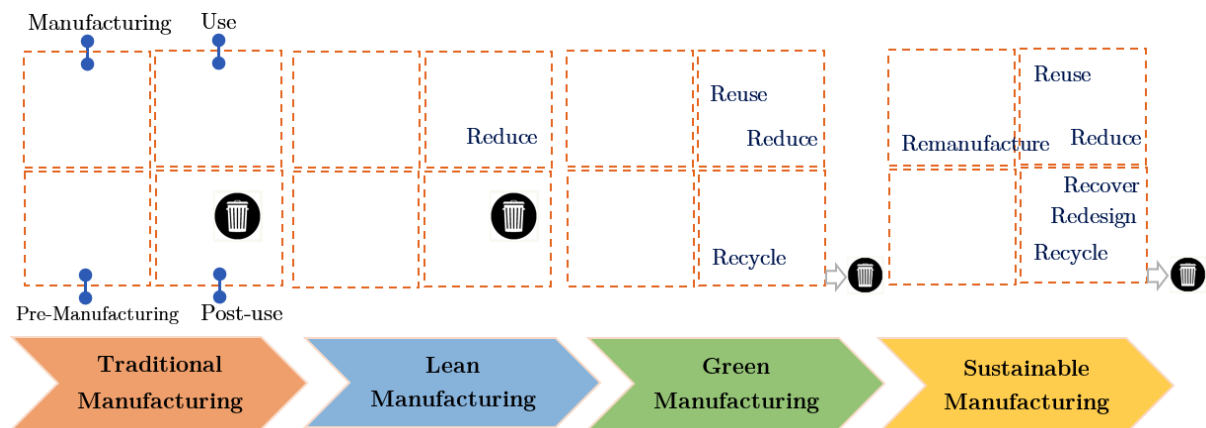


Figure 2.5 Evolution of manufacturing strategies (Badurdeen and Jawahir, 2017)

Figure 2.5 represents the evolution of manufacturing strategies for the entire lifecycle covering four lifecycle stages with value recovery through the various 'R's and associated gradual reduction in landfill through each strategy. The four lifecycle stages considered are pre-manufacturing, manufacturing, use, and post-use (Badurdeen and Jawahir, 2017).

### 2.2.2 Conventional Manufacturing

After reviewing the conventional design process and recent design perspectives, (Ahmad et al., 2018) wrote that traditional product design focuses on product functionalities, quality, and cost for meeting customer requirements whereas sustainable product design (SPD) systematically views the entire product life cycle for functionality, environment, and economic performance.

SPD stresses the importance of the entire life cycle of a product from its raw material selection, conceptual and structural formation, manufacturing, and usage to its end-of-life, reuse, and recycle.

In CM processes, product-specific environmental and economic impacts are largely considered during the design stage (Haapala et al., 2013; Shao et al., 2017; Yuan et al., 2012). The emerging shift towards design for AM is because it enables improved sustainability performance through better utilization of performance indicators and helps to achieve more than just product-specific objectives environmental and ecological impacts through improved quality, enhanced overall performance, avoiding warranty returns and minimizing defect probabilities, and so on.

In the sustainability evaluation of most conventional manufacturing processes, it is necessary to know relevant considerations. Some of these considerations include faster tool path, improved surface quality, material removal rate, tool life, tool geometry, and cutting conditions in milling (number of teeth, depth of cut, tool inclination, and cutting speed) that will be used to characterize the cutting operation. Besides, large amounts of material must be removed in roughing operations, and tool path selection and optimization are key to increase productivity (Kiswanto et al., 2014; Langeron et al., 2004; Prat et al., 2012; Rauch et al., 2009). The above-mentioned and many more considerations should be identified and categorized to appropriate sustainability dimensions.

### **2.2.3 Additive Manufacturing**

Additive manufacturing (AM) is a name given to technologies that build 3D objects by adding layer upon layer (joining) of materials, unlike subtractive manufacturing. This is producing a 3D object directly from a digital model (3D model data) (Gebisa and Lemu, 2017; Gupta et al., 2012; Nathan, 2015; Sossou et al., 2018). The material can be plastic, metal, or concrete. 3D printing was first used by industries to produce prototypes. Today this technology is applied to build in-flight production components of aircraft. It also enables the design and production of monolithic structures which is converting an assembly and several structures into one piece (Nathan, 2015).

According to various literature, AM shows a better advantage of addressing issues of sustainable manufacturing than conventional manufacturing (CM) processes. To mention some, it gives opportunities for weight and cost reduction, minimized the negative environmental and social impact, especially when there are high complexity and customization of parts. Additive manufacturing enables the design and production of multi-material, multifunctional, monolithic, and customized parts which will indirectly related to our resource consumption and subsequent environmental, economic, and societal impact. This technology allows direct printing from CAD model, optimization, prototype manufacturing, flexibility, complexity, product customization,

resource efficiency to realize an optimized object, operation-related issues, supply chain (Gardan and Schneider, 2015; Gebisa and Lemu, 2017; Huang et al., 2013; Jared et al., 2017; Nathan, 2015; Sossou et al., 2018; Tang et al., 2016; Thompson et al., 2016).

Besides the advantages mentioned, common limitations of AM include high cost of machine and material as an initial investment, poor surface finish (cause for extended post-processing activities), less production volume and building speed (the reason for low productivity), dimensional stability, uncertainty in final part mechanical properties, expensive AM equipment and material, the impact of powder on human health, etc. Supplementing post-processing activities helps to improve the microstructure, reduce porosity and to finish surfaces, reduce roughness and meet geometric tolerance. However, several strategies are also being implemented to minimize these challenges. (Bikas et al., 2016; Bourell et al., 2017; Frazier, 2014; Giffi et al., 2014; Gupta et al., 2012; Hapuwatte et al., 2016; Huang et al., 2013; Sossou et al., 2018; Vaneker, 2017; Yang and Zhao, 2015).

Research efforts into the *design for additive manufacturing* (DfAM) have been mostly dedicated to part's design, which is a requirement for a better industrial adoption (Sossou et al., 2018). Since AM is capable of manufacturing fully functional assemblies requiring a few or no assembly operations, there is a need for DfAM methodologies tackling product developments more holistically, and which are, therefore dedicated to assembly design.

### 2.2.3.1 Types and applications of additive manufacturing

Since the shift towards design for additive manufacturing, different types of additive manufacturing have found wider applications. These types of additive manufacturing methods vary based on application or type of products to manufacture, operation and working principles, raw materials utilized, etc. Widely known types of AM are 3D Printing, Electron Beam Melting (EBM), Wire Deposition Techniques (WDT), Blown Powder Deposition (BPD), Wire Arc Additive Manufacturing (WAAM), Stereolithography (SLA), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Laser Metal Deposition (LMD), Electron Beam Melting (EBM), Fused Deposition Modeling (FDM), Ultrasonic Additive Manufacturing (UAM), Hybrid Manufacturing (HM).

Applications of additive manufacturing processes and corresponding materials are summarized and reported in Table 2.2 adapted from (Giffi et al., 2014), a study on opportunities of 3D printing in the automotive industry. Based on applications already made using additive manufacturing and applications that will be potentially manufactured in the future, the summary is presented in two as current and future respectively. Identifying and categorizing in such a manner will help companies to easily select process/material/application combinations when the need for additively manufactured products found wider acceptance and interest.

Table 2.2 Application of Additive Manufacturing in Automobiles (Giffi et al., 2014)

	AM technology	Materials	Automobile systems	Applications
<b>Current</b>	SLS	Polymers	Exterior trim	Bumpers, wind breakers
	SLM, EBM	Aluminum alloys	Fuel Handling	Pumps, valves
	FDM, Inkjet, SLS, SLM	Polymer, wax, hot work steels	Manufacturing process	Prototyping, customized tooling, investment casting
	SLM	Aluminum alloys	Exhaust / emissions	Cooling vents
<b>Future</b>	SLS, SLG	Polymers	Interior and sitting	Dashboards, seat frames
	SLS, Inkjet, SLM	Polymers, Aluminum alloy	Wheels, tires, suspension	Hubcaps, tires, suspension springs
	SLS	Polymers	Electronics	Embedded components (sensors, single part control panels)
	SLM, EBM	Aluminum, Steel Alloys	OEM components	Body in white
	SLM	Aluminum alloys	Frame, body, doors	Body panels
	SLM, EBM	Aluminum, Titanium alloys	Powertrain, drive train	Engine components

Table 2.2 Reports application of the different types of AM in automobile systems and applications. Moreover, possible materials for corresponding processes and applications are relevant to know. Advancements in manufacturing processes, especially in additive manufacturing processes are becoming a better opportunity to assure sustainability through design for additive manufacturing. These advancements in manufacturing processes help achieve the desired geometry with better sustainability performance.

For example, UAM is a hybrid form of manufacturing, which is primarily used for metals permits novel functionalities such as multi-material structures with embedded componentry to be realized (Friel and Harris, 2013). It is defined as a solid-state additive manufacturing process that sequentially bonds metal foils together using ultrasonic metal welding (UMW), layer by layer, and integrates Computer Numerical Control (CNC) machining to remove material to create the desired geometry (Friel and Harris, 2013; Sossou et al., 2018; Wolcott et al., 2016). Moreover, the other method, HM is suggested to avoid the current variability and finish quality concerns. It is a combination of AM with other traditional techniques such as milling and forging. For example ultrasonic additive manufacturing, an advanced technology based on AM, using sound, that combines additive (ultrasonic welding) with subtractive (CNC milling) techniques to create metal parts (Giffi et al., 2014). Enhancing sustainability through these types of methods is possible through achieving high design flexibility, allows efficient utilization of combined AM and CM methods.

### 2.2.3.2. Materials for additive manufacturing

As a growing trend, mostly design of materials for 3D printing is important (mostly titanium 6Al-4V powder is utilized). It was a widely used alloy originally used for forging. Thus, it is necessary to tweak (improve) these alloys for other processes. There must be an effort to expand the portfolio of available materials for AM. New processes of combining AM with nanomaterials are under development, intending to increase tensile strength, electrical conductivity, hardness, and impact strength (Giffi et al., 2014). Moreover, an increase in strength without a corresponding increase in weight could potentially lead AM to even be used to make the body in white for future automobiles.

Another important material is carbon fiber which is used to make lightweight auto components such as fenders, car roofs, and windshield frames through conventional techniques. AM starts using it after the first commercial AM device that uses this material is launched. A low density, high strength, and corrosion-resistant Titanium has strong appeal in the automotive industry.

Moreover, materials used as filament materials by 3D printing for layer-by-layer object building include Polylactic acid (PLA), thermoplastic polyurethane (TPU), Nylon, ABS, and PC which can often be mixed with coloring dye and other additives (Davis et al., 2019).

Thus, (Giffi et al., 2014; Gupta et al., 2012; Sossou et al., 2018) reported the following limitations and challenges about materials for additive manufacturing;

1. Availability of materials (low-cost materials). Typical materials are polymers and some metals. Some waxes and papers for some niche applications too.
2. Dimensional accuracy and quality of the surface finish of the final parts produced through AM are not always on par with those made with conventional manufacturing processes.
3. Most components manufactured through AM require some form of post-processing, which involves removing unused material, improving surface finish, and removing support material. Its impact is high in large components and it is necessary to improve the post-processing quality and reliability for AM to use it on large scale.
4. The volume of production: The economics of AM is limited to low volume production: AM having low production speeds (build speed) to produce requirements of a large number of components, improving building rates through AM technology of SLM has been an important focus in recent years.
5. Manufacturing large parts: Limited build envelopes of current AM technologies. Large components of automotive such as body panels still have to be attached through processes



such as welding or mechanical joining processes. Low-cost AM technologies that can support larger build sizes for metal parts have to be developed. Make to manufacture products with no limitation in size.

6. The material properties of the produced products are relatively poor.
7. Talent shortage: AM-specific skills are necessary for the area of CAD design, AM machine making, operation, and maintenance, raw material preparation, and management.
8. Intellectual property concerns:
9. Accessibility and safety related to the complexity of operations.

### **2.3 Current trends of Design and Manufacturing**

During sustainable product development, it is essential to consider the purpose of the approach (design of a new product, product, or process improvement), and to address all stages of the product life cycle (from pre-manufacturing to post-use). According to (Buchert et al., 2014), it must also be taken into account

- The point of application (task classification, design, embodiment and detail design, production planning);
- Sustainability which is based on the Triple Bottom Line (TBL) approach;
- The type of data processed (qualitative, quantitative, or semi-quantitative);
- Method user (product manager, designer, production planner or user);
- Abstraction layer (product, process, requirement, component, service).

According to (Ahmad et al., 2018), traditional product design focused on product functionalities, quality, and cost for meeting customer requirements whereas sustainable product design (SPD) systematically views the entire product life cycle for functionality, environment, and economic performance. Moreover, (Moktadir et al., 2018; Shao et al., 2017) also supported understandings on sustainable design and manufacturing as it is a creation of manufactured products that use processes to minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound.

Figure 2.6 represents the necessity to develop new frameworks to achieve sustainable goals with minimum complexity and give structure to the knowledge of sustainability without compromising its technical and economic feasibility (Peralta Álvarez et al., 2017). Based on the 3E perspective (economic, ecological, and equity), four of the life cycle phases (design, modeling simulation, optimization, and assessment), it is mentioned that a variety of optimization techniques (either multi-objective or multi-criteria) utilized in researches on optimization of

machining parameters: traditional mathematical methods (linear and non-linear programming), and new methods include statistical methods (ANOVA, fuzzy set and Taguchi) and metaheuristics (genetic algorithms, search methods such as simulated annealing and Tabu search), artificial neural networks or evolutionary algorithms.

Current design methods are divided into three as; (Yang and Zhao, 2015)

1. Development of a general framework that initializes design from the perspective of functional achievement;
2. Development of a method to better synthesize functional requirements and process knowledge simultaneously; and
3. Development of an analytical method for design rationalization and multifunctional optimization.

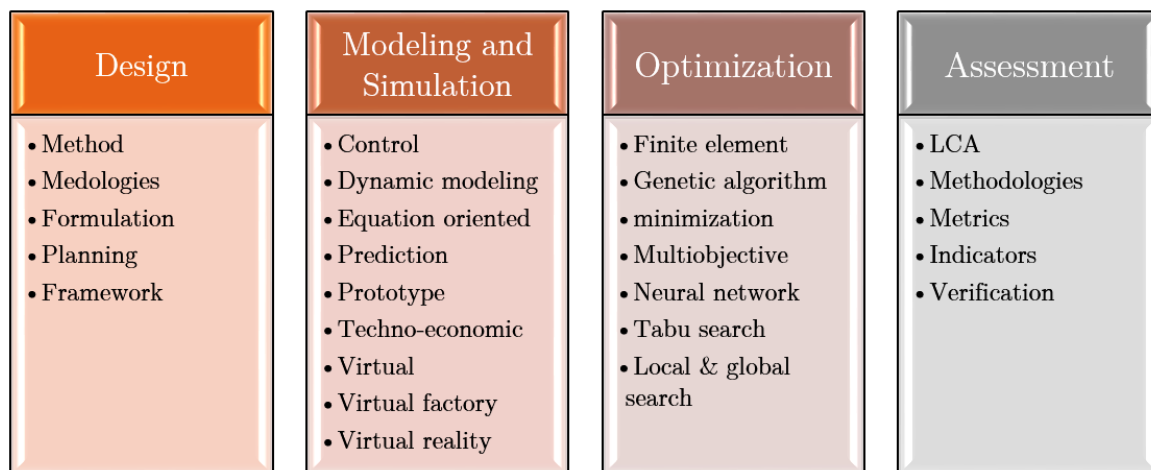


Figure 2.6 Key areas related to design and development (Peralta Álvarez et al., 2017).

Design for sustainability, as shown in Figure 2.7 (Jawahir et al., 2006), contains basic elements and sub-elements of product design for sustainability. It is shown that there are six major sustainability elements, several sub-elements mentioned in the Figure, and equal weighting is displayed. But according to similar other reviews, this list is not exhaustive and needs consideration of other sub-elements that can be categorized into the three main sustainability dimensions.



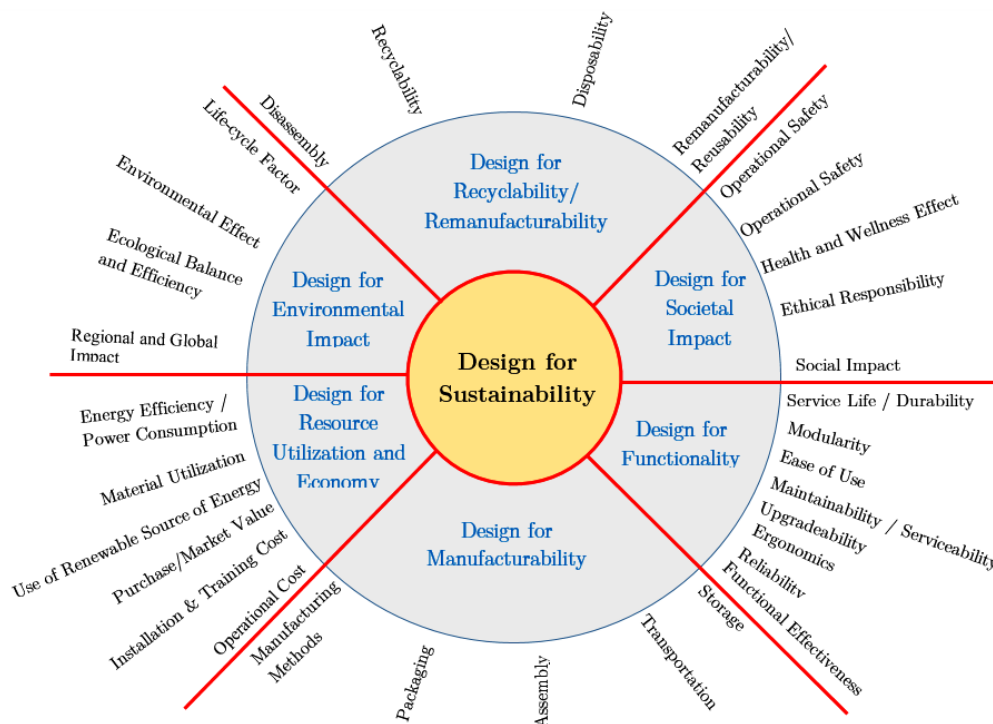


Figure 2.7 Basic elements and sub-elements of product design for sustainability (Jawahir et al., 2006)

Mentioned as the product sustainability wheel, Figure 2.7 represents six major product sustainability elements and several sub-elements. Besides developing approaches for quantification, it is necessary to fully study their effects on product sustainability.

Thus, it is necessary to understand the principles of concurrent engineering, identify possible products for additive manufacturing and assess existing trends of design and manufacturing.

### 2.3.1 Concurrent Engineering

Concurrent Engineering (CE) is defined as “a systematic approach to the integrated, simultaneous design of products and their related processes, including manufacture and support. It is intended to stimulate product designers/developers to consider all elements of the product life cycle in the early stage of product development (Xu et al., 2007).

In concurrent engineering, all product life cycle stages are taken into account when making decisions and are intended to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements and using the right people together at the right time to identify and resolve design problems (Tang et al., 2000; Xu et al., 2007).

Concurrent engineering includes designing for assembly, availability, cost, customer satisfaction, maintainability, manageability, manufacturability, operability, performance, quality, risk, safety, schedule, social acceptability, and all other attributes of the product. Characteristics of concurrent engineering include reduced cycle time, overlapping of functional activities, collaboration in functional decisions, concurrent evolution of system and component decisions, critical sequencing. This is contrasted with a traditional serial process in which the design team finishes its work before the drafting department prepares and releases the drawings, at which time manufacturing starts. Because of the overlapping of functional activities, cycle times may be greatly reduced and decisions become highly interdependent.

CE is an ideal environment for product development with objectives of improving quality, reducing costs, compressing life cycle times, increasing flexibility, raising productivity and efficiency, and improving the social image. The most effective approach in implementing CE is design-for-X (DFX) (Huang, 1996).

### **2.3.2 Products for Additive Manufacturing**

Several products are in the market developed by different companies and researchers. These products are witnesses that the research on AM is becoming popular and highly relevant as compared to existing conventional processes. Some justifications for this include:

- General Electric (GE) uses AM technologies of SLS and SLA in its preproduction and design processes across its functional areas (design, engineering, and manufacturing) with its rapid prototyping department producing test models of more than 20,000 components.
- Dana, a supplier of driveline, sealing and thermal-management technologies for OEMs utilize a combination of rapid prototyping and simulation to create prototypes that can be tested to form and fit.
- BMW used AM in direct manufacturing to make the hand tools used in testing and assembly with better ergonomic design and 72% less than the weight of traditional hand tools. It is reported that it resulted in overall cost reduction (58%) and reduction in project time (82%).
- FORD saved millions of dollars in product development costs (cylinder heads, intake manifolds, and air vents) by using AM to create prototypes and skipping the need for tooling.
- Airbus and GE have incorporated AM to produce lightweight versions of components such as nacelle hinge brackets and complex parts used in unmanned aerial vehicles (Giffi et al., 2014).

- Delphi, a tier 1 automotive supplier, uses SLM instead of traditional machining of Aluminum diecasting to make diesel pumps. Besides making a single component (drastically reducing part count and simplifying the assembly process), overall production cost, which is less prone to leakage, is reduced.

Today, both OEMs and suppliers use AM to enhance existing operations: for the following reasons;

- To support the decision-making at the design stage.
- To establish quality at the reproduction stage.
- To develop custom tools.
- To reduce overall time to market.

### **2.3.3 Trends of design and manufacturing**

Future trends in design and manufacturing must consider beyond requirements of success of product design, development, and manufacturing as reported by (Johansson, 2002). These requirements include the integration of suppliers, process performance, project leadership, management system, customer involvement, effectiveness of product concept development (fit with market need and fit with firm competencies), market, and financial performance but didn't boldly show consideration of environment as a key factor.

To achieve better sustainability performance of manufacturing processes for better success in product design and development, it is also necessary to address associated limitations. For example, the US Unit Process Life Cycle Inventories (UPLCI) and the European CO2PE are making efforts to address the limitation of manufacturing processes as the weakest aspects of the life cycle database (process changes or technology updates)) (Haapala et al., 2013).

Moreover, the major issues associated with current design and manufacturing which can be taken as an advantage are increased awareness for sustainable products and social responsibility, and ecological concerns from users and industries. According to (Gupta et al., 2012; Haapala et al., 2013; Moldavska and Welo, 2017), the development of sustainable products is pinned on resource consumption, pollution, safety, and risk on human and ecosystem, durability, and performance. Concerning social responsibility and ecological concerns, United Nations (UN) defines sustainability development goals set by minimizing environmental impacts, economical and safe for employees and communities.

Industries should devise a solution to solve these above-mentioned issues related to design and manufacturing through a balanced consideration of all three dimensions of sustainability. Once these issues are solved it will be easy to keep them highly competent and reputable on the

current market system (Ahmad et al., 2018; Ceschin and Gaziulusoy, 2016; Eastwood and Haapala, 2015; Madan Shankar et al., 2017; Zhang et al., 2013). Moreover, since 80% of sustainability impacts are decided on the design stage, lead researchers of the manufacturing sector focus on possibilities of realization of any design and propose a strategy to sustainability and cleaner production objectives.

The progress of advanced manufacturing on sustainability improvement along with the whole life cycle covers six themes as reported by (Jin et al., 2017). These themes and descriptions are reported in Table 2.4.

Table 2.4 Progress of advanced manufacturing on sustainability improvements for PLC (Jin et al., 2017)

S.No.	Theme	Description
1.	Design theory and methodology for sustainability with advanced manufacturing.	<ul style="list-style-type: none"> <li>• Which one is efficient? Additive Manufacturing (AM) or Subtractive Manufacturing (SM)?</li> <li>• Issues of sustainability for AM (uncertain performance of products and parts during the usage phase and overextended life span because of low maturity of technology).</li> </ul>
2.	Energy efficiency assessment and control of mechanical manufacturing systems.	<ul style="list-style-type: none"> <li>• Conventional MMS (mechanical manufacturing systems) utilize a huge amount of energy and have very low efficiency.</li> <li>• Identify abnormal energy consumption caused by incorrect part dimensioning, or erroneous cutting conditions.</li> <li>• Optimization of energy consumption and quality of a product as objectives (multi-objective decisions).</li> <li>• Energy consumption at the shop floor level (processing, set-up, transportation, standby, overhead by auxiliary equipment such as lighting and HVAC systems)</li> </ul>
3.	Parameter optimization for advanced manufacturing and remanufacturing.	<ul style="list-style-type: none"> <li>• To model resource use, cost, and performance as objectives.</li> <li>• The finite Element data analysis approach to establish mathematical relations between the process variables and the cutting force and power consumption was analyzed using a weighted analysis technique which confirms that optimizing the cutting angle can result in reduced cutting force, which lowers power consumption.</li> <li>• Studies on effects of different cutting parameters such as spindle rotation speed, cutting speed, feed rate, depth of cut on MRR (material removal rate) on specific energy consumption (SEC) in turning.</li> <li>• Decision-making rules were proposed to assist CNC machine tool practitioners in selecting optimal cutting parameters for minimum energy consumption.</li> <li>• Used normal boundary intersection with a multivariate mean square error approach for simultaneously resulting, minimizing roughness, and maximizing MRR.</li> </ul>

	<ul style="list-style-type: none"> <li>• A multi-objective parameter optimization model is proposed for maximizing energy efficiency and minimizing production cost by using Adaptive Multi-Objective Particle Swarm Optimization algorithm.</li> <li>• For reduced energy consumption and improved machining quality in turning processes, a multi-objective multi-pass turning operations model for ensuring quality and improving energy efficiency was formulated.</li> <li>• To reduce energy consumption and improve thermal efficiency in arc welding processes, FSGA (Fitness Sharing Genetic Algorithm) is used to obtain the optimal welding current and welding velocity for the model.</li> <li>• To maximize reliability and minimize process cost, a dual-objective remanufacturing model is utilized by integrating the quality evaluation of returned products in the total process.</li> </ul>
4. Low fossil carbon process planning and scheduling	<ul style="list-style-type: none"> <li>• Process plan specifies what manufacturing resources and technical operations/routes are needed to produce a product.</li> <li>• Effective scheduling of all jobs on machines.</li> <li>• To reduce makespan and total energy consumption for shop floor management, a multi-objective optimization method for energy-efficient flexible shop scheduling is proposed. Genetic algorithm is employed to simultaneously optimize makespan and total energy consumption at the shop floor level.</li> <li>• To minimize the energy consumption of the machining plan, a mathematical model integrating process planning and scheduling based on NLPP (nonlinear process planning) is established. The model is solved by a genetic algorithm-based approach to effectively find the optimal process plan and machine allocation for each job as well as for simultaneously scheduling when alternative process schemes of each job NLPP were needed.</li> <li>• To optimize process planning and process scheduling for remanufacturing, the optimal core portfolio is determined (acquisition quantities and remanufacturing quantities based on the tradeoffs between environmental and economic benefit). The conformity of the decision-making process of the remanufacturer is checked.</li> </ul>
5. Integration of supply chain innovations and advanced manufacturing	<ul style="list-style-type: none"> <li>• Supply chain innovations, such as resource planning, electronic data exchange, and the adoption of radio frequency identification (RFID) in logistics, have contributed to the complexity and globalization of the current economy.</li> <li>• Impacts of AM on sustainability are based on the four stages of the product life cycle (product and process redesign, material input processing, make-to-order component and product manufacturing, and closing the loop).</li> <li>• A real-time dynamically, reconfigurable, and sustainable operation architecture for function block-based dynamic cellular manufacturing product-service system (DCM-PSS) for achieving manufacturing and</li> </ul>

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	<p>service integration. Its implementation will improve the sustainability of economic performance and social performance.</p> <ul style="list-style-type: none"> <li>• Transportation distances and modes of distribution of raw material and finished parts (Boeing data) have been estimated.</li> </ul>
6. Sustainable innovation for product-service systems (PSS).	<ul style="list-style-type: none"> <li>• PSS is to offer customers physical products and/or services that can help to improve energy savings and value-added services.</li> <li>• All aspects of sustainability (environment, economic and social factors) are considered.</li> <li>• Researches must be done on how to develop, implement and monitor sustainable models for PSS, and how sustainable design methods and tools can be integrated into PSS to deliver sustainability.</li> <li>• A configuration and operation architecture for block-based dynamic cellular manufacturing product-service system (DCM-PSS) and studied key techniques of configuration and operation of DCM-PSS.</li> <li>• Value uncaptured is proposed as a new perspective for sustainable business model innovation and developed four forms of value uncaptured: value surplus, value absence, value missed, and value destroyed. The framework was validated for six firms.</li> </ul>

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To sum up, it is necessary to revolutionize the design and manufacturing sector through the implementation of smart manufacturing (industry 4.0) which will make more data available for better decision-making through consideration of systemic tradeoffs among relevant indicators. Thus, the current trend is towards an integration of product-service operations to maximize the environmental, economic, and social sustainability of advanced manufacturing.

## 2.4 Decision-making methodologies and Sustainability Frameworks

### 2.4.1 Decision making and methodologies

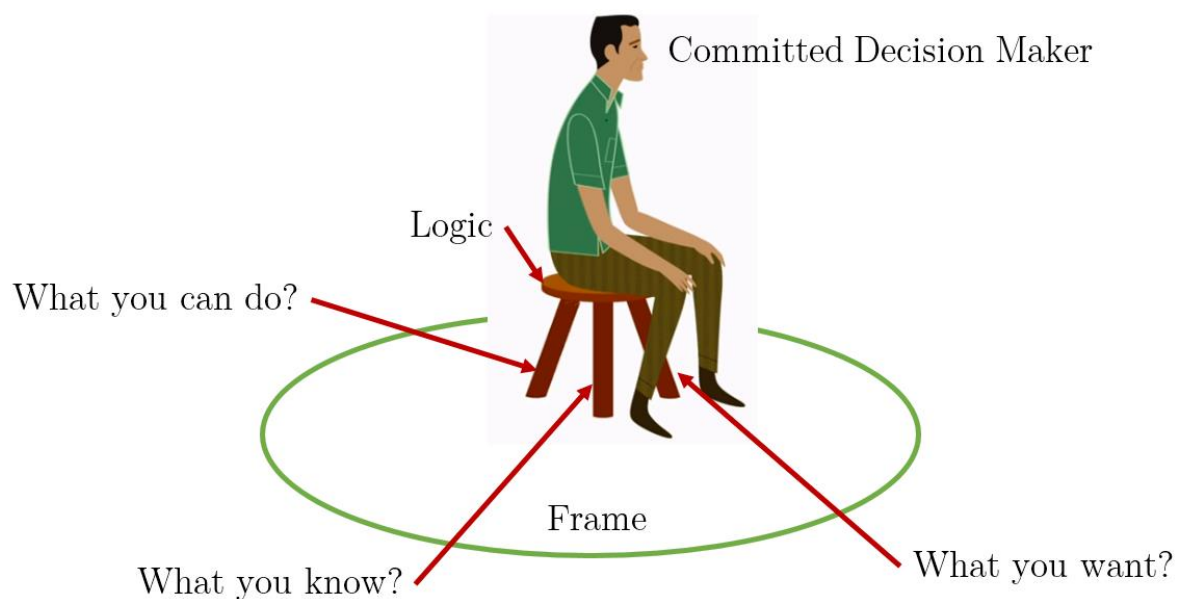
Works of literature to date have tried to address issues of sustainability in CM processes in different contexts for various applications but none were able to propose comprehensive frameworks and strategies to address it fully. One key issue is the lack of exhaustive consideration of performance indicators (PIs) throughout the product life cycle (PLC) and balanced consideration of the three dimensions of sustainability is missing (Peralta Álvarez et al., 2017). For example, (Reich-Weiser et al., 2008) tried to develop PIs focused on energy use, climate change, and non-renewable resource consumption. However social dimension is entirely missing and there are still unconsidered yet vital sustainability indicators that fully characterize sustainable manufacturing.

Few efforts accounted for sustainability considerations within the design for manufacturing and assembly (DfM) due to limitations on analytical methods within the ability to accurately integrate eco-design principles into DfMA tools. To reach sustainable manufacturing goals,

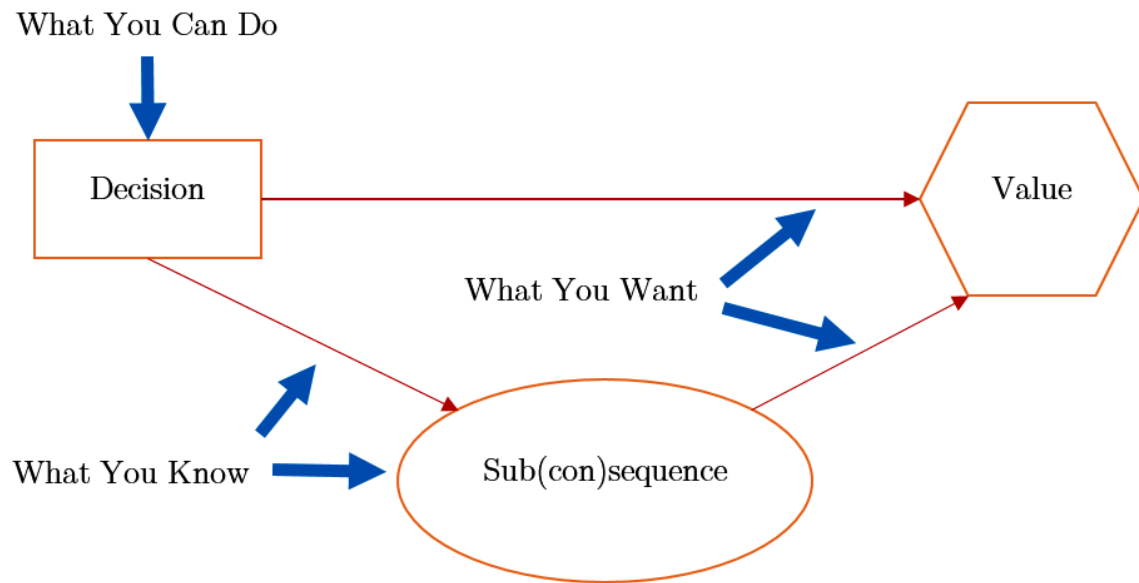
current researches generally fall into four categories: manufacturing process and equipment, manufacturing systems, changes in life cycle paradigms, and education (Haapala et al., 2013). Thus, it is necessary to consider engineering decision-making to define the goal generate a possible solution, and predict preference.

In a chapter by (National Academy of Sciences, 2004) about basic tools for applied decision theory, the quality of a decision and the decision process is represented in Figure 2.8. A committed decision-maker must know what to do, what one wants, and what one knows in a single framework.

As shown in Figure 2.8a, the first element is to know what the decision-maker can do in the face of alternatives to be considered. The second element of the decision basis is information (i.e., what links the alternatives to what will ultimately happen), which can be in the form of models describing the field of concern in the decision. The seat is the logic acting on the decision basis to produce a course of action. The person seated on the stool is the decision-maker who has stated the decision to be made. The ground on which the stool is placed represents the frame developed for the decision situation.



(a) The quality of a decision



(b) The decision process

Figure 2.8 The decision basis (National Academy of Sciences, 2004)

The rectangular box in Figure 2.8b showing the decision diagram represents a decision node, an action under the control of the decision-maker. Ovals represent uncertainties or, in some cases, calculations. Finally, hexagons represent the value node, with inputs showing what the decision-maker values. Arrows into any node show what its value depends on, either functionally or in the sense of conditioned probability. Arrows into decision nodes show what is known when the decision is made.



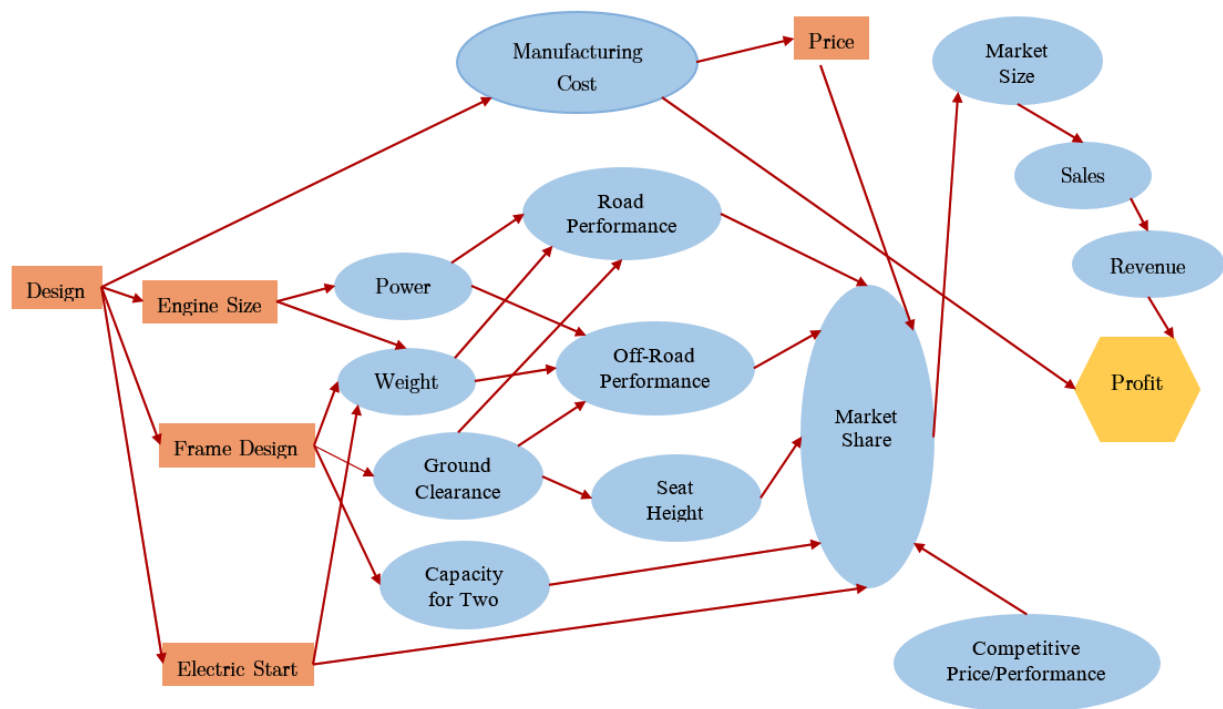


Figure 2.9 Decision diagram for design of a dual-sport motorcycle (National Academy of Sciences, 2004)

An example of a decision diagram for the design of a dual-sport motorcycle is shown in Figure 2.9. It is important to note that the manufacturing cost will be known when the price decision has been made.

A good decision gives all the available alternatives one has, all the information one possesses, and the preferences once assess. The quality of a decision rests on having framed the decision correctly, that is, answering the right question, understanding the issues (knowledge), what can be done (options), and what you want (desired outcomes).

According to (Bereketli and Erol Genevois, 2013; Brunes and Monteiro de Carvalho, 2015; Dufrene et al., 2013), several studies were made in establishing methodologies and sustainability frameworks in environmental product design but didn't provide a precise framework for the identification of the relevant improvement strategies related to part characteristics. Furthermore, they proposed a hierarchy with a goal of weighting customers' requirements by considering cost, quality, and environmental concern and many alternatives which weren't comprehensive to address sustainability. One of the most recent reviews by (Ahmad et al., 2018), witnesses that researches in engineering failed to provide appropriate tools to assist decisions on manufacturing systems. Currently, it is focusing on balancing the three dimensions of sustainability. More studies are needed to develop new methodologies to describe, analyze, evaluate and optimize sustainability performance metrics for manufacturing processes and/or systems.

Summary of several studies listed below to support decision making for sustainable manufacturing using modeling and simulation have been reported by (Shao et al., 2017). However, none of these approaches utilized reusable modular knowledge description of sustainable process and analytics for analysis and decision making.

1. An interactive tool that jointly combines simulation models and data to support human and environmentally friendly decision-making for SM systems regarding investment and product design.
2. An integrated system that combined simulation and energy analysis tools.
3. Method for analysis of INDustrial energy systems (MIND) to optimize energy use in foundries.
4. Simulation model of an automotive paint shop that simulated different input parameter options to determine the one with the least CO<sub>2</sub> emission.
5. A simulation model for precision casting operation to study issues associated with integrating production systems, process energy, and facility energy to improve manufacturing sustainability.

A very extensive review on advantages, disadvantages, and applications of the eleven most widely known multicriteria decision-making analysis (MCDA) methods is reported by (Velasquez and Hester, 2013). A summary is reported below to take as background information for an informed preference of a decision-making methodology for the intended study.

### **1. Multi-Attribute Utility Theory (MAUT)**

It is an extension of Multi-Attribute Value Theory. This method helps how to incorporate risk preferences and uncertainty into multicriteria decision support methods, assists decision analysis in real-world, used to decide the best course of action in a given problem by assigning a utility to every possible consequence and calculating the best possible utility, it takes uncertainty into account (a major advantage of this method) and finally, it is comprehensive and can account for and incorporate the preferences of each consequence at every step of the method. The main disadvantage of MAUT is that it is data intensive where large data input is necessary.

The major applications of MAUT include are applied to assist selection of the location of a global manufacturing facility, used in real-world application to analyze risk preferences with regards to forest land use in Australia, used in industry risk assessments, a model is developed using MAUT incorporating technical, socio-cultural, and institutional criteria for decisions about the scope of implementation and sustainability of decision support systems, utilized in the selection of a dewatering system, applied in economics, financial, actuarial, water management, energy management, and agricultural problems.

## **2. Analytic Hierarchy Process (AHP)**

AHP allows the use of pairwise comparisons, which are used both to compare the alternatives concerning the various criteria and to estimate criteria weights. Major advantages of this method include ease of use, its use of pairwise comparisons can allow decision-makers to weight coefficients and compare alternatives with relative ease, it is scalable, and can easily adjust in size to accommodate decision-making problems due to its hierarchical structure and it is not as data-intensive as MAUT. But it still requires intensive data.

As a major disadvantage, this method experienced a problem of interdependency between criteria and alternatives. Due to the approach of pairwise comparisons, it can also be subject to inconsistencies in judgment and ranking criteria and it doesn't allow (individuals) to grade one instrument in isolation, but in comparison with the rest, without identifying weaknesses and strengths. One of the biggest criticism is that the general form of AHP is susceptible to rank reversal.

The review mentions common applications such as decision making within Hawaii's Fisheries, organizational performances of telecommunication companies (with BSC), urban water systems in Nigeria, in transport infrastructure appraisals. Such as Railway. Moreover, it has been used in performance-type problems, resource management, corporate policy and strategy, and planning.

## **3. Fuzzy Set Theory (FST)**

FST is another multicriteria decision analysis (MCDA) that allows for imprecise input by taking into account insufficient information and cost-benefit analysis for environmental projects. The main disadvantage is the difficulty to develop and the need for numerous simulations before use. Applications are presented in water resource planning and supply chain management, engineering, economics, environmental, social, medical, and management.

## **4. Case-based Reasoning (CBR)**

The major advantage of CBR is that it is not data-intensive, requires little maintenance, can improve over time, can adapt to changes in the environment. Two major disadvantages include sensitivity to inconsistent data and require many cases. It finds applications in business, vehicle insurance, medicine, and engineering design.

## **5. Data Equipment Analysis (DEA)**

This method of DMA can be used to measure relative efficiencies of alternatives against each other and with all other alternatives. It is capable of handling multiple inputs and outputs and also able to analyze and quantify efficiency. Assuming all input and output data are exactly known and not dealing with imprecise data are the two common disadvantages of this method. It finds wider applications in economics, medicine, utilities, road safety, agriculture, retail, and business problems.

## **6. Simple Multi-Attribute Rating Technique (SMART)**

SMART is one of the simplest forms of MAUT. It requires two assumptions of “utility independence and preferential independence”. It conveniently converts important weights into actual numbers and requires less effort than MAUT. As the major disadvantage is the procedure for determining work is not convenient considering the complicated framework. It finds applications in environmental, construction, transportation and logistics, military, manufacturing, and assembly problems.

## **7. Goal Programming (GOP)**

It is a pragmatic programming method that can choose from an infinite number of alternatives. Its capacity to handle large-scale problems and its ability to produce infinite alternatives provide a significant advantage over some methods. The major disadvantage of this method is its inability to weight coefficients. For example, AHP is used to properly weight coefficients. Production planning, scheduling, health care, portfolio selection, distribution system design, energy planning, water reservoir management, timber harvest scheduling, wildlife management problems are the major applications of GOP.

## **8. ELimination Et Choix Traduisant la REalité (ELECTRE)**

It is an outranking method based on concordance analysis which takes into account uncertainty and vagueness as a major advantage. As a disadvantage, its process and outcome can be hard to explain in layman terms and the lowest performance under certain criteria are not displayed. Application areas include energy, economics, environmental, water management, and transportation problems.

## **9. Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE)**

This method of MCDA is easy to use, doesn't require the assumption that the criteria are proportionate and used in the ranking of alternatives. As a disadvantage, it doesn't provide a clear method by which to assign weights and it requires the assignment of values but doesn't provide a clear method by which to assign those values. It finds applications in environmental management, hydrology and water management, business and financial management, chemistry, logistics and transportation, manufacturing and assembly, energy management, and agriculture.

## **10. Simple Additive Weighting (SAW)**

In this method, a value function is established based on a simple addition of scores that represent the goal achievement under each criterion, multiplied by the particular weights. It can compensate among criteria and is also intuitive to decision-makers and can be performed without the help of computer programs. The disadvantage includes that all the values of the criteria should be maximizing, should be positive and the estimates yielded by SAW don't always reflect the real situation. The result obtained may not be logical, with the value of one particular criterion largely differing from those of other criteria. Common applications mentioned include water management, business, and financial management.

## **11. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)**

It is an approach to identify an alternative that is closest to the ideal solution and farthest to the negative ideal solution in a multi-dimensional computing space. It is a simple process, easy to use, and programmable, it can confirm the answers proposed by other MCDM (many of the uses seen in literature) and review other methods or stand on its own as a decision-making tool (due to its simplicity and ability to maintain the same amount of steps regardless of problem size). As a common disadvantage, its use of Euclidean distance doesn't consider the correlation of attributes and it is difficult to weight attributes and keep the consistency of judgments, especially with additional attributes. Applications include supply chain management and logistics, design, engineering and manufacturing systems, business and marketing management, environmental management, human resource management, and water resource management.

Besides the above-mentioned MCDA methods, it is also useful to supplement the following recommendations and implemented methodologies for a deeper understanding of decision-making methodologies and sustainability frameworks for better sustainability consideration.

A study on advanced manufacturing process by (Jin et al., 2017) reported that new optimization and modeling algorithms provide potential to improve conventional manufacturing processes by systematically considering the tradeoffs among materials, energy, emissions, quality, etc. especially in the implementation of smart manufacturing (industry 4.0) to make more data available for better decision making.

For sustainable manufacturing through technological improvement, process-based analytical models play an important role in quantifying the inputs such as material and energy and outputs such as products, emissions, and waste (Yuan et al., 2012). Material flow analysis and energy flow analysis are the two widely adopted tools to quantify and track the material/energy flows in manufacturing. Moreover, (Eastwood and Haapala, 2015) tried to develop a sustainable assessment methodology to both improve the accuracy of existing approaches in identifying the sustainability impacts of a product and to assist manufacturing decision-makers. Methodology developed utilizes unit process modeling and life cycle inventory techniques.

A systematic decision-guidance methodology is introduced by (Shao et al., 2017) that uses sustainable process analytics formalism (SPAF) developed at the National Institute of Research and Technology. The methodology provides step-by-step guidance for users to perform sustainability performance analysis using SPAF which supports data querying, what-if-analysis, and decision optimization for sustainable metrics.

Manufacturing products impact all three facets of sustainability: economy, environment, manufacturing, transportation, use, and disposal (Ahmad et al., 2018). Besides, 80% of sustainability impacts are decided at the design stage, which leads researchers to focus on the manufacturing sector and propose a strategy for sustainability and cleaner production objectives.

In conclusion, understanding the advantages, disadvantages, and applications of these widely known MCDA methods is highly relevant to tune researchers' preferences for methodologies for the intended application where preference is done based on minimizing disadvantages and maximize opportunities of each method.

#### **2.4.2 Analytic Hierarchy Process**

Analytic Hierarchy Process (AHP) is one of the most powerful multicriteria decision-making methods developed by Prof. Thomas L. Saaty (Saaty and Vargas, 2012). It is a general theory of measurement that is used to drive ratio scales from both discrete and continuous paired comparisons in multilevel hierarchic structures (Haapala et al., 2013; Saaty and Vargas, 2012). The method uses pairwise comparisons to simplify preference ratings among decision criteria and provides measures of judgment consistency and drives priorities among criteria and alternatives.

The method is also employed in decisions related to strategic planning, resource allocation, business, and public policy, program selection, and much more.

According to (Mu and Pereyra-Rojas, 2017), AHP is helpful to evaluate qualitative and quantitative criteria on the same preference scale, has wider acceptance and applications, easier hierarchical modeling or problem structuring, adopts verbal judgments, and allows verification of consistency. Moreover, it is incorporated in the user-friendly software (Expert Choice, Super choice, Decision Lens), which shows that it finds various software options and can be used in conjunction with other methods. The graphical interface on Expert Choice allows better visualization of the impacts of changes

There are steps to follow in applying AHP as proposed by (Ishizaka and Labib, 2009; Saaty and Vargas, 2012; WANT and BAD, 1990). First problems are decomposed into a hierarchy of criteria and alternatives, then the problem is analyzed by treating criteria (criteria 1, 2, 3 ...n) and possible alternatives (alternatives: 1, 2, 3 ...n). Thus, it is important to state the objective, define or identify the criteria and finally pick the alternatives. To generate a final decision using AHP, relevant steps are briefly explained.

## 1. Problem structuring

A hierarchic or a network structure is needed to represent the problem, as well as a pairwise comparison to establish relations within the structure through a selection of relevant criteria, subcriteria, sub-subcriteria, arrangement of each criterion.

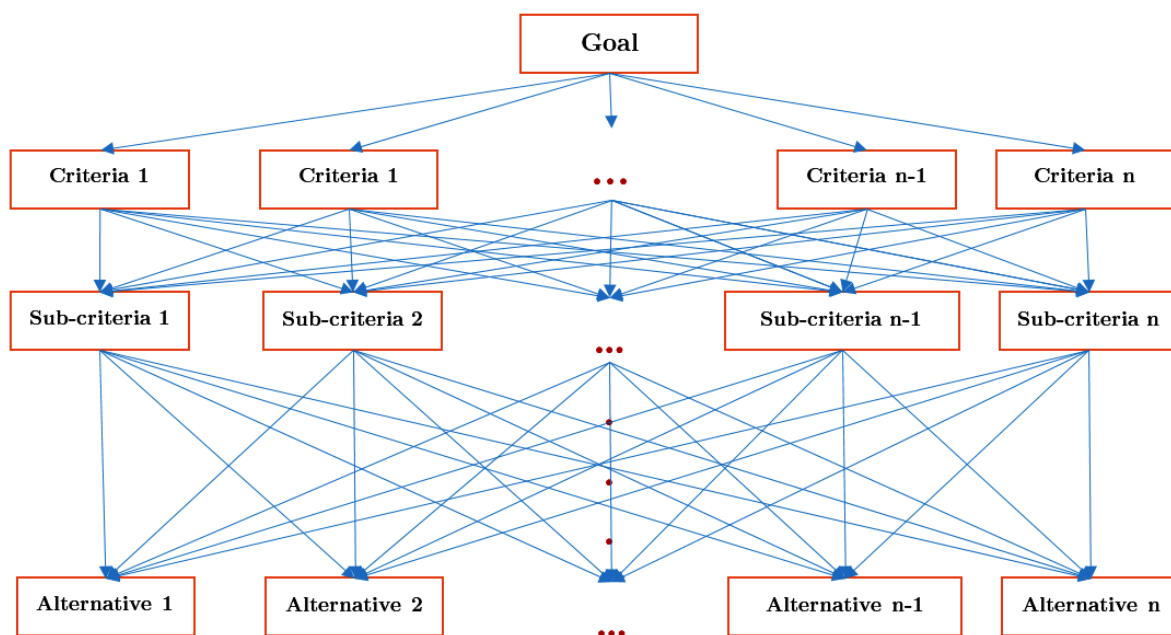


Figure 2.10 A three-level hierarchy [Modified by Authors] (Saaty and Vargas, 2012)

The first step in applying AHP is structuring the decision-making problem in existing criteria or subcriteria (whenever available) and existing alternatives to using the method for solving decision-making problems of finding the “best” alternative among the given sets of alternatives. For example, Figure 2.10 shows a three-level hierarchical structure of DM problem with four criteria and three alternatives. As shown in Figure 2.10, AHP considers several factors simultaneously, allowing for dependence and feedback and making numerical tradeoffs to arrive at a synthesis or conclusion.

## 2. Problem modeling

In decision making using AHP, the most creative task in making a decision is deciding what factors to include in the hierarchic structure. In constructing hierarchies one must include enough relevant criteria, subcriteria, and alternatives. The elements being compared should be homogeneous.

## 3. Pair-wise comparisons

AHP is used to drive ratio scales from both discrete and continuous paired comparisons in multilevel hierarchic structures. Comparisons may be taken from actual measurements or from a fundamental scale that reflects the relative strength of preferences and feelings.

The method provides relative judgment of two alternatives, allows comparison is recorded in a positive reciprocal matrix as shown in *Equation 2.1*. But it is important to note that there is no need to provide numerical value, the same units must be used between alternatives. Comparison between elements  $j$  and  $j$  is represented by  $a_{ij}$ . The order in which comparisons entered in the matrix may affect successive judgment and if perfectly constant, the transitivity rule holds for all comparisons.

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & \dots & a_{ij} & \dots \\ \dots & \dots & \dots & \dots \\ a_{n1} & \dots & \dots & 1 \end{bmatrix} \quad \text{Equation 2.1}$$

$$a_{ij} = a_{ik} \cdot a_{kj}$$

## 4. Judgment scales

For evaluation, AHP needs fundamental comparison scales (Saaty scale) as shown in Table 2.6 due to its pair-wise comparisons. To drive priorities, verbal comparisons must be converted to numerical ones using Saaty scales between 1 and 9, used in most applications.



Table 2.6 Fundamental comparison scale (Saaty and Vargas, 2012)

Intensity of importance	Definition	Explanation
1;2	Equal importance; weak	Two activities contribute equally to the objective.
3;4	Moderate importance; moderate plus	Experience and judgment slightly favor one activity over another.
5;6	Strong importance; strong plus	Experience and judgment strongly favor one activity over another.
7;8	Very strong; very, very strong	An activity is favored very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence of favoring one activity over another is of the highest possible order of affirmation.

The explanation section in Table 2.6 reports how favorable one preference is over the other. In selecting the intensity of importance, the decision-maker makes informed judgments based on evidence and the experience of decision-makers.

## 5. Normalization and priorities vector derivation

This step considers steps of finding sets of priorities where the relative importance of each element of the hierarchy from the evaluations obtained from the previous steps. One of the methods to develop priorities, the following three steps; as shown in *Equations 2.2 to 2.4*.

1. Sum the elements of each column j.
2. Divide each value by its column sum.
3. Mean of row i.

Verification of results can be done based on the judgment given at the pairwise comparison step. Equation 2.2 represents the eigenvalue method which is used to determination of maximal eigenvalue using matrix A, priority,  $w_i$ .

$$A.w_{ij} = \lambda.w_{ij}$$

*Equation 2.2*

Eigenvector will give you a ranking of priorities from a pairwise matrix. To solve for the eigenvector, raise the pairwise matrix to powers that are successfully squared each time, the row sums are then calculated and normalized. The normalized pairwise comparison matrix is shown in Equation 2.3.

$$A_{norm} = \begin{bmatrix} 1 & w_{12} & \dots & w_{1n} \\ w_{21} & \dots & w_{ij} & \dots \\ \dots & \dots & \dots & \dots \\ w_{n1} & \dots & \dots & 1 \end{bmatrix}$$

Where

$$w_{ij} = \frac{a_{ij}}{\sum_{i=1, j=1}^n a_{ij}}, \forall_{i, row \ j, column} \quad \text{Equation 2.3}$$

Then, the criteria weight vector is the average value of each entry is a normalized vector.

$$W_i = \begin{bmatrix} W_i \\ \dots \\ \dots \\ W_n \end{bmatrix} \quad W_i, \forall_{i=1 \text{ to } n} = \frac{\sum_i^n w_{il}}{n} \quad \text{Equation 2.4}$$

## 6. Consistency

Redundant comparisons are made to improve the validity of responses since decision-makers may be uncertain or may make poor judgments for the comparison of some elements. Consistent reciprocal matrix, the largest Eigenvalue is equal to the number of comparisons, or  $\lambda_{\max} = n$ .

Where  $\lambda_{\max}$  represents the maximum eigenvalue is determined using *Equation 2.5*. Then he gave a measure of consistency, called Consistency Index (CI) as deviation or degree of consistency using the following formula in *Equation 2.6*. The CI is related to the eigenvalue method and its value depends on maximum eigenvalue and matrix dimension depending on the problem.

$$\lambda_{\max} = \sum_{i,j=1}^n \left( \frac{W_i}{w_{ij}} \right) \quad \text{Equation 2.5}$$

And

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad \text{Equation 2.6}$$

The appropriate consistency index is called a random consistency index (RI). A randomly generated reciprocal matrix using scale 1/9, 1/8, ..., 8, 9 is selected by Prof. Saaty and gets the RI to see if it is about 10% or less. The average random consistency index of sample size 500 matrices is shown in Table 2.7.

$$CR = CI / RI \quad \text{Equation 2.7}$$

A random index (RI) is the average CI of 500 randomly filled matrices. Other researchers run simulations for different matrix sizes. But results show that the RI values are different but close to Saaty's suggestion.

Table 2.7 Average random consistency index (Saaty and Vargas, 2012)

n	1	2	3	4	5	6	7	8	9	10
Random consistency index (RI)	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The Consistency Ratio (CR) is the ratio of the coherence index calculated on the matrix corresponding to the judgments of the decision-maker and the RI of a matrix of the same dimension. Once CI is determined, a consistency ratio (CR) is can be determined using *Equation 2.7*. If the value of CR is smaller or equal to 10%, the inconsistency is acceptable. If the Consistency Ratio is greater than 10%, experts' judgment needs revision.

## 7. Incomplete pairwise matrix

A pairwise comparison is performed on each level after decomposing the structure of this problem. The number of pairwise comparisons for n criteria is given by *Equation 2.8*.

$$\frac{(n^2 - n)}{2} \quad \text{Equation 2.8}$$

But large number of comparisons or poor judgement are common causes of inconsistency and it is possible to delete comparisons from large matrices without affecting results. The minimal number of comparisons is n-1, one for each row or column of the pairwise comparison. To calculate these pairwise comparisons, the transitivity rule can be used as represented in

$$a_{ij} = a_{ik} \cdot a_{km} \cdot \dots \cdot a_{vj}.$$

## 8. Aggregation

This step leads to the determination of global priority from each local priority. Additive aggregation with normalization of the sum of the local priorities to unity.  $P_i$  is the global priority of the alternative i and  $l_{ij}$  is the local priority and  $W_j$  is the weight of the criterion j. It may also need a sustainability analysis where input data are slightly modified to observe the impact on results. This ensures the reliability of the results obtained.

To recap, AHP method allows to decompose a complex problem into a hierarchical system into different levels where different criteria, subcriteria, etc. are associated to determine the most

relevant alternative, depending on the priority given to each of the criteria taken into account consideration. To do so, this section presented relevant steps categorized as a selection of criteria and subcriteria selection to structure the problem, modeling the problem, construction pairwise comparison matrices, driving priorities using Saaty's fundamental comparison scales, priority derivation through consistency verification, and aggregation.

### 2.4.3 Methodologies needed for the sustainability of manufacturing

In the current sustainable manufacturing research, significant efforts are put on the development of metrics and tools for environmental performance analysis of manufacturing processes. But little work has been done in the system level of thinking for the development of an approach to improve the overall sustainability of manufacturing (Yuan et al., 2012) which also considers economic and social dimensions.

An operation research (OR) optimization model has decision variables, constraints that have to be satisfied, and an objective function to be optimized. A feasible solution is an instantiation of values from corresponding domains of decision variables that satisfy all the constraints. Among all feasible solutions, an optimal solution is the one that makes the object minimal or maximal, as required (Shao et al., 2017). But models lack the modularity of modern object-oriented languages, so they tend to become difficult to modify or extend. Therefore, for the objective of assuring sustainability, the best (optimal) solution with modularity should be developed.

To understand several efforts in applying tools or methods in sustainable manufacturing, it is necessary to mention some of the methodologies that contribute sustainability of manufacturing processes. A study by (Jin et al., 2017), mentions the following important inputs.

- Multi-objective decision methodologies to optimize energy consumption and quality of products as objectives.
- Utilization of Finite Element data analysis in conventional manufacturing methods for analyzing the relationship between process variables, cutting force, and power consumption to minimize power consumption by reducing cutting force. Moreover, a dual objective remanufacturing model is utilized to maximize reliability and minimize process cost.
- Adaptive Multi-Objective Particle Swarm Optimization (AMOPSO) algorithm is used to propose a multi-objective parameter optimization model for maximizing energy efficiency and minimizing production cost and Fitness Sharing Genetic Algorithm (FSGA) is used to reduce energy consumption and improve thermal efficiency in arc welding processes.

- Nonlinear Process Planning (NLPP), a mathematical model integrating process planning and scheduling, is used to minimize the energy consumption of the machining plan.
- Dynamic Cellular Manufacturing – Product Service System (DCM-PSS) is used to integrate manufacturing and service which will improve the sustainability of economic and social performance (a closed loop of product and process design. Material input processing, make-to-order, and product manufacturing).

Moreover, different approaches, tools, and frameworks are reported by various studies focusing on system thinking, quantify material and energy flow, and so on.

- A combined approach of the principle of sustainable manufacturing system thinking in the form of system dynamics to develop a conceptual model is considered by (Zhang et al., 2013) to understand the complex interaction of factors within the defined system.
- DEMATEL, one of the MCDM tools, is utilized to evaluate the influential sustainable manufacturing practice among 22 common SM practices are categorized for the three pillars of sustainability (Madan Shankar et al., 2017). The analysis revealed that “promoting 6R” became the first influential and “improved process performance” became the least influential.
- Design for sustainable manufacturing (DfSM) framework is developed (Haapala et al., 2013) which aggregates international issues, contemporary issues, and innovative products, reconfigurable manufacturing systems, manufacturing strategies, performance measurements, and flexible organizational management into a single index using a weighted sum approach.
- Material flow analysis and energy flow analysis are the two widely adopted tools to quantify and track the material/energy flow in manufacturing (Yuan et al., 2012).
- A sustainable assessment methodology (which utilizes unit process modeling and life cycle inventory techniques) is developed by (Eastwood and Haapala, 2015) to improve the accuracy of existing approaches in identifying the sustainability impacts of a product and also to assist decision-makers in manufacturing.
- Sustainable Process Analytics Formalism (SPAF) is developed to provide step-by-step guidance of users to perform sustainability performance analysis which is introduced by (Shao et al., 2017) as a systemic decision-guide methodology. It supports data querying, what-if-analysis, and decision optimization for sustainable metrics.

- Value uncaptured is proposed as a new perspective for sustainable business model innovation and developed four forms of (validated for six firms) value uncaptured: value surplus, value absence, value missed, and value destroyed.

Even though the objectives of the studies are not directly related to sustainable manufacturing, the following methods and tools have been reviewed to support better performance for researches with similar scope in conventional manufacturing.

- An analytical method is presented to define Cutter Workpiece Engagement (CWE) for toroidal and flat-end cutters during semi-finished milling of sculptured parts (Langeron et al., 2004).
- Computation of Adapted Tool Shape (CATS) is proposed by (Chaves-Jacob et al., 2009) to compute and optimize the tool shape to avoid the problem of interferences during the flank milling of a non-developable ruled surface.
- Statistical tolerance analysis of over-constrained mechanisms is considered by (Beaucaire et al., 2012) is used to compute defect probability to avoid warranty returns and manage the rate of out-of-tolerance products in production that may lead to assembly line stoppages and/or the discarding of out-of-tolerance mechanisms. Moreover, it is reported that tolerance analysis can be used to evaluate a predicted quality level in the design stage. By knowing the dimension tolerances and functional requirements, the defect probability of an existing design can be computed.
- Certification of tool paths is introduced by (Duc et al., 2006) to ensure a reduction in machining time and cost by considering all constraints imposed by the manufacturing process. Criteria classified as criteria of constraint (geometry, use of a cutting tool, machining time) and criteria of performance (machining cost – part cost, machining time, tool wear).
- The approach of Graph Theory and Matrix Approach (GTMA) is utilized by (Moktadir et al., 2018) to determine relative impacts of identified drivers by researchers (knowledge about the circular economy, customer awareness, leadership, and commitment from top management). In this study, AHP is recommended to rank factors in future relevant studies and use the top-ranked factors in a GTMA approach.

To conclude, in this section selected scientific study outcomes are reported to support understandings of system-level thinking and utilization of decision-making methodologies despite the type of process as conventional or additive manufacturing. These approaches, methodologies, tools, and frameworks are reported based on a wider understanding of energy optimization,

understanding the relationship between process variables, time and cost-related issues for economic performance, use, and post-use actions and requirements, etc. This will be used as background information to further establish comprehensive decision-making methodologies for sustainable performance.

## **2.5 Summary and implications**

According to the literature review presented, there is a subjective understanding of sustainability itself. The understanding depends on the scope of each study or the priorities of industries or manufacturers. In the first parts of the review, it is presented that more integration of ecodesign into the product design and development was common. This integration was focusing on minimizing adverse environmental impacts throughout the product's life cycle. This consideration omits the economic and social dimensions of sustainability to fully characterize it. Of course, some considerations of human priorities are also mentioned but the ultimate goal was still to minimize environmental impacts. Thus, the current challenge identified includes avoiding this subjective understanding which won't be affected by the scope and priority of industries and at the same time balanced consideration of sustainability dimensions.

The other relevant information extracted from this literature survey is the quantification and consideration of sustainability performance indicators for the entire product life cycle. Most studies utilize repeated and commonly used decision-making factors such as productivity, cost, energy consumption, etc. Moreover, based on concepts mentioned about sustainability, there is a common understanding taken from key references and gaps considered for possible focus in this study.

The first and foremost identified gap and possible area of focus is the subjectivity of sustainability. According to literature surveys, current research trends are being viewed from vague sustainability perspectives about considering all the three dimensions. In the design and manufacturing process, conflicts between dimensions of sustainability were probable during simultaneous considerations which require application and development of multicriteria decision making. In sustainable product design and development, the establishment of methodologies and proposal of new models, indicators, and strategies is needed for balanced and concurrent consideration of performance indicators to avoid subjectivity issues.

In considering the three dimensions of sustainability, it is recommended that the balanced and comprehensiveness of each dimension (with the 3E perspective) are highly valuable. Moreover, incomplete consideration of sustainability performance indicators for each dimension has led to the inefficient implementation of environmental, economic, and social dimensions, even if it seems performance evaluation is done. Moreover, since there exists an incomplete list of sustainability performance indicators, another intensive review is needed to propose a

comprehensive list of sustainability performance indicators. Once the list of indicators identified, it is necessary to use different methodologies to consider tradeoffs among various performance indicators.

It is also discussed that there is a need to develop new methodologies to describe, analyze, evaluate and optimize sustainability performance metrics for manufacturing processes and/or systems. Development of metrics and tools is widely found more for environmental performance than for all dimensions, including economic and social. Thus, new metrics or sustainable performance indicators should be developed to improve the overall sustainable performance of manufacturing.

Opportunities of design for additive manufacturing should also be exploited through proper understandings of conventional and additive manufacturing process requirements. Also, the trends in design and manufacturing show that there is better integration of suppliers, process performance, leadership, system management, customer involvement, etc. This can be understood from recent signs of progress in the design and manufacturing of products where new methods of modeling and optimization are being developed to consider systematic tradeoffs between indicators. Moreover, the current trend of automation and data exchange in industry 4.0 will help to make more data available for better decision-making.

In the section where an assessment of existing decision-making approaches and methodologies done, one can understand that there is an increasing trend in accommodating balanced and concurrent consideration of sustainability dimensions. But Among the reviewed methodologies, it is observed that the analytic hierarchy process is the most powerful decision-making methodology which finds wider application and acceptance. It uses pairwise comparison, simple preference rating, and consistency verification and drives priorities among decision criteria. It allows simultaneous consideration of indicators and makes numerical tradeoffs to arrive at a synthesis or conclusion.

Therefore, it is necessary to study and analyze the possibilities of minimizing or avoiding the subjective understanding of sustainability by providing a comprehensive list of sustainability performance. Thus, the main focuses of this study are; analysis of the sustainability performance of the additive manufacturing processes, development of a comprehensive list of sustainability performance indicators, and finally proposes of an application for sustainability performance evaluation of processes in manufacturing engineering products using a multi-criteria decision-making methodology of AHP.



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## Chapter 3

### Research Design and Methodology

#### 3.1 Research Design

This study focuses on developing a comprehensive multicriteria decision-making methodology for sustainability by proposing a new list of sustainability performance indicators (SPIs) and exploiting opportunities of additive manufacturing for sustainability performance. This has been done through an exhaustive literature survey (Chapter 2) to explain past, current, and future trends of sustainability in manufacturing. The survey and assessment are done on keywords of sustainability, sustainable manufacturing, sustainability performance of additive manufacturing processes, product life cycle considerations, design and manufacturing trends, and multicriteria decision-making methodologies. The three main steps of the whole study are explained below.

The first step in this study is an assessment of the sustainable performance of additive manufacturing processes (Chapter 4). The assessment result is highly relevant for designers who are focusing on design for additive manufacturing. Being aware of opportunities of additive manufacturing for better sustainability performance over conventional manufacturing, a designer will come up with avoiding issues related to poor sustainability performance in conventional manufacturing processes.

The second step focuses on developing a comprehensive list of sustainability performance indicators (SPIs). To achieve this, a wider literature survey and analysis have been done to identify existing gaps associated with sustainability itself, sustainable manufacturing, as well as design and manufacturing trends. Based on the review, a new list and description of SPIs is first developed and validated for its comprehensiveness through comparison to the ten existing indicator sets and guidelines (Chapter 5). The development of SPIs has been done by considering all the three dimensions of sustainability throughout the life cycle of a product.

The third and final stage is to develop a comprehensive multicriteria decision-making methodology by using an analytic hierarchy process (AHP) to evaluate the sustainability performance of an engineering product when manufactured via alternative manufacturing processes such as conventional and additive manufacturing (Chapter 6). As an application, manufacturing of Faceshield bracket using three different methods of manufacturing is considered; Injection molding, 3D printing, and laser cutting. A comparison will be developed and a ranking for better sustainable performance of each process is developed to conclude the study. Figure 3.1 shows the overall approach followed to accomplish the objectives.

### **3.2 Research Framework**

The research framework of the dissertation is based on consideration of outcomes of literature review and current trends of product design and manufacturing as well as the need for sustainability. The research framework is presented in Figure 3.1 which displays research methods and tools, research objective, and research outputs.

The research framework shown in Figure 3.1 represents the following four main steps.

1. An intensive literature review to identify possible gaps existing in sustainability performance indicators. The literature survey is done based on topics associated with sustainability, sustainable manufacturing, and trends associated to design for additive manufacturing, etc.
2. The sustainability performance of additive manufacturing is analyzed through comparative research on the various literature surveyed.
3. Proposal of a generic performance tree for the comparison of manufacturing processes from a sustainable development point of view.
4. The development of a multicriteria decision-making methodology is proposed by using Analytic Hierarchy Process (AHP).

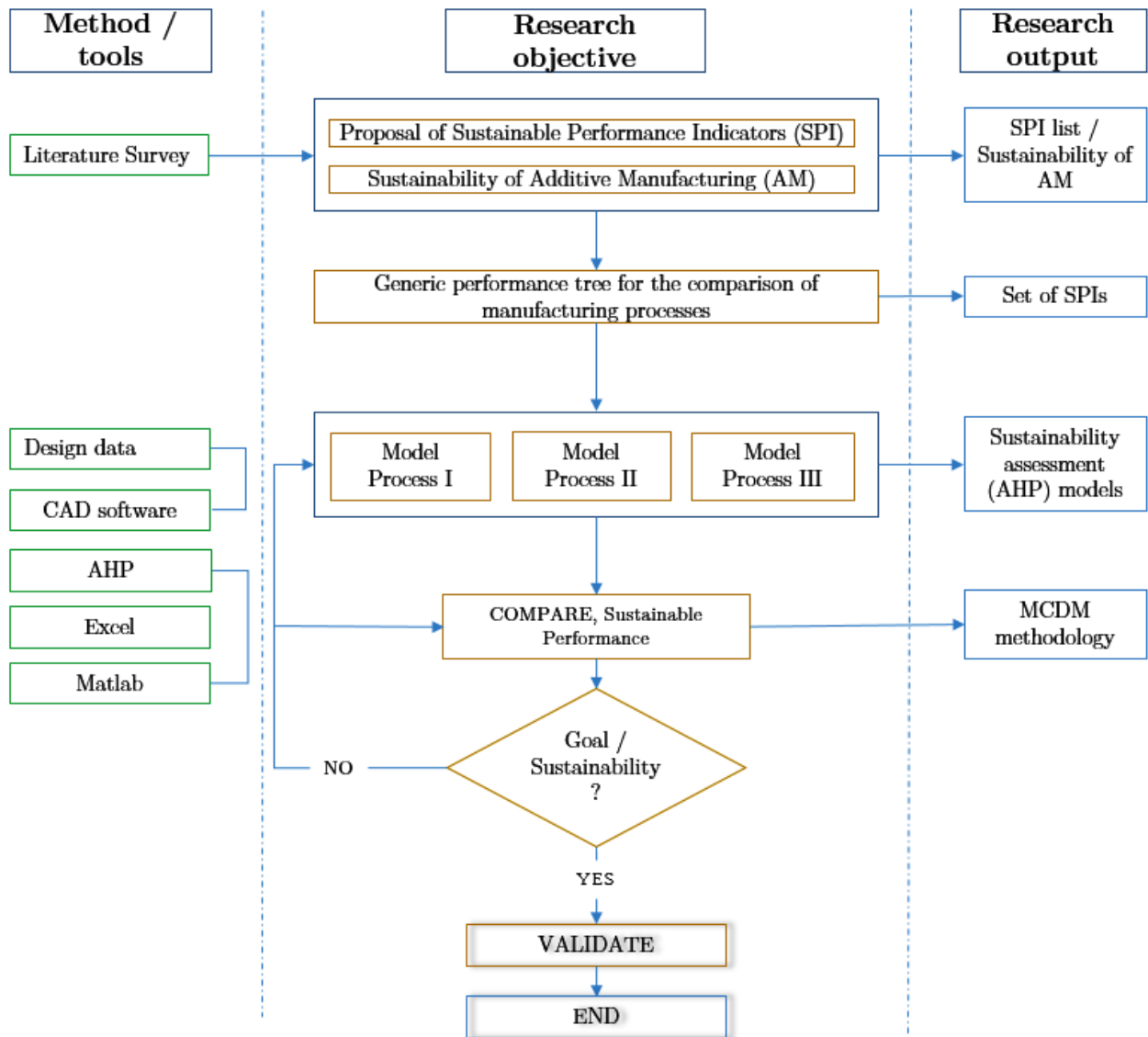


Figure 3.1 Research framework

The proposed conceptual framework and methodology are then applied to an engineering application. In this case by considering Faceshield bracket manufacturing as an application. As a first step, the proposed generic sustainability performance tree is pruned to the study's framework. Then an evaluation of each basic performance indicator selected from information at our disposal or through models we proposed is done. Finally, AHP analysis is performed to compare the three manufacturing processes used to manufacture the three different types of Faceshield brackets.

### 3.3 Research Methodologies

As clearly shown in the research framework, a method of an intensive literature review is utilized. The literature review indicated gaps and gives perspective on immediate the future of



sustainability of manufacturing processes as well as product design and development. Thus, this section reports approaches followed to achieve research objectives.

### **3.3.1 Literature Review**

The author has gone through more than 157 publications collected from scientific journals, conference proceedings, books, company newsletters, original equipment manufacturer product specifications, research and innovation outputs, and related topics from different websites. Moreover, assessment of existing indicator sets and guidelines are reviewed to use it as validation for exhaustiveness of sustainable performance indicators.

The first highly relevant topic assessed was on identifying the existing list of sustainability performance indicators through topics on subjective understandings of sustainability itself and incomplete consideration of indicators for existing dimensions of sustainability. Then, assessment on sustainability of manufacturing process is done through identification of existing challenges and opportunities of additive and conventional manufacturing process. This literature survey and assessment is done based on the trends of design and manufacturing. In the process of the evaluation sustainability performance of additive manufacturing, a survey has been done on products manufactured by additive manufacturing for reference and perspectives of design and manufacturing.

The second relevant information gathered from this literature survey is about decision-making methodologies and frameworks, and then, among the reviewed methods, selection of Analytic Hierarchy Process (AHP) as the most widely accepted, powerful decision-making methodology to use for developing the intended multicriteria decision-making methodology for sustainability evaluation.

### **3.3.2 Application**

For this study, a Faceshield bracket manufactured using three methods of manufacturing; injection molding, 3D printing, and laser cutting is selected as an application. Relevant data for decision-making are collected from product designers and manufacturers. Besides, collection of relevant features from a process perspective and features of Faceshields manufactured using the three methods is done. The primary data collected from the selected application will be used as input for developing the decision-making methodology. The data collection scheme was made and proposed based on the three dimensions of sustainability. Explicit data gathered during and after manufacturing of the Faceshield that have an impact on either two or three of these dimensions of sustainability is assigned to the dominant dimension based on experts' judgment.

### **3.3.3 Sustainability Performance Indicators**

For this problem, secondary data are associated with additive manufacturing and its performance towards sustainability as compared to conventional manufacturing. The basis for considerations of product life cycle factors, SPI factors, and constraints on data types are briefly described below.

#### **3.3.3.1 Product Life Cycle factors**

In consideration of product life cycle (PLC) factors both for additive and conventional manufacturing processes, identifying each factor as pre-design, design, manufacturing, and use and post-use stages. The pre-design factors are associated with material availability, extraction, and processing, packaging, and storage of materials and essential requirements of a good product design. Manufacturing factors consider process input and outputs, infrastructure, machinery and tools, warehouse and inventory, health and safety, and issues related to workers and staff. The use and post-use factors include consideration of the 6R concept, functional requirements of the product and user-product relationship, quality, and packaging. The last product life cycle factor considers logistics which deals with associate impact and emissions as well as the location of shop floor and cites for end-of-life operations.

#### **3.3.3.2 SPI factors**

Selection of the most relevant indicator from the list of sustainability performance indicators proposed is done since it was not necessary to consider all. Each of the selected SPI factors considered is categorized within the three dimensions of sustainability: environment, economic and social.

#### **3.3.3.2 Constraints**

The constraints on data type vary depending on the type of process selected as CM and AM. The data type mainly will be needed in the modeling of both processes. These include but not limited to;

- The number of processes that are needed to produce the product.
- The number of sub-processes that are needed (if any) to successfully produce the product?
- The items that flow in and out of the system.
- The metrics that are needed to be calculated for each process.
- The overall sustainability metrics for the whole process.

### **3.3.3.3 Tools and Methods**

To develop the intended multicriteria decision-making methodology, Analytic Hierarchy Process (AHP) is utilized as the main tool. But to complete the intended objective, Microsoft Excel, Matlab, AutoCAD and CATIA are used.

## Chapter 4

### Analyzing Sustainability Performance of Additive Manufacturing

#### 4.1 Introduction

According to definitions given in Chapter 2, Additive manufacturing (AM) is a name given to technologies that build 3D objects by adding layer upon layer (joining) of materials, unlike subtractive manufacturing. This is producing a 3D object directly from a digital model (3D model data) (Gebisa and Lemu, 2017; Gupta et al., 2012; Nathan, 2015; Sossou et al., 2018). Moreover, Additive Manufacturing is a method that finds different definitions according to different works of literature. For example, it is known as an umbrella term for different manufacturing methods that will help to manufacture complex three-dimensional shapes by layering up materials (Wiberg et al., 2019). Unlike conventional manufacturing technologies, AM is known for minimized manufacturing constraints, which gives opportunities for designers to produce highly optimized, more intricate valuable engineering products with minimized weight and resource consumption.

Additive manufacturing is used to build parts or products that can't be manufactured by conventional methods where a goal of minimizing material consumption can easily be achieved through it (Gardan and Schneider, 2015). Weight reduction and subsequent cost reduction will have better sustainable performance and AM will help to manufacture products optimized to achieve these objectives.

The main categories of the research in the field of DfAM are system design, part design, and process design. System design defines components suitable for AM and components' boundaries, the part design focuses on design and validation of parts suitable for AM and process design preparation of the manufacturing process respectively.

#### 4.2 Inspiration

The main inspiration to study and analyze the sustainability performance of additive manufacturing is the current shift from design for manufacturing (DfM) to design for additive manufacturing (DfAM). The main goal of DfAM was to reduce manufacturing costs by improving product quality by addressing the manufacturing constraints. The optimized design is finding a compromise between size, shape, or part topology and utilization of as minimum material as possible while ensuring the overall performance of the part is not fully realized by conventional manufacturing processes (turning or milling).

In response to the development of new materials, improved design methods, and societal demand for manufactured products, the concept of DfM can't fully incorporate these demands into the development of more sustainable products. The possible paradigm shift from DfM to DfAM is analyzed by (Gebisa and Lemu, 2017) to realize design optimization. Besides, the impacts on the realization of optimum design, and accommodation of the requirements for product sustainability are assessed.

Moreover, redesign of engineering parts is done to gain one or more advantages of AM over CM processes. These advantages include a shorter life cycle of production, complex parts production, reduce the total number of parts, design for functionality, design parts to be multifunctional, lightweight, topological optimization, design for ease of manufacturing, cost-saving, reduced weight, power consumption, optimal build direction when a part is built with the variable layer thickness for different 3D manufacturing systems, build time, lead-time, cost savings from the speed of near net-shaped fabrication and waste material savings and lower assembly costs (DebRoy et al., 2018; Džugan and Novy, 2017; EPAM, 2015; Hasan and Rennie, 2008; Vishnu Prashant Reddy et al., 2018; Zwier and Wits, 2016). In AM, alloy powders are commonly used as feedstock materials in the laser and electron beam assisted AM processes to build a part with a composition/property gradient that is difficult to produce with conventional processes.

Identifying challenges in applying AM was also helpful to be aware of and minimize or avoid these limitations of challenges. Thus, the development of the process will focus on tackling these challenges. Getting the best build orientation is one of the challenging design aspects for additive manufacturing since it has a large impact on the final part quality (Zwier and Wits, 2016). Limitations on part size, process-specific effects, high-temperature gradients, etc. Manufacturing high-quality powder remains a critical challenge due to its high surface area and susceptibility to oxidation. Moreover, the characteristics of the additively manufactured parts are significantly influenced by the characteristics of the feedstock materials. High-quality powders are expensive because of the high cost of the fabrication process such as plasma-rotating electrode process (PREP) and low yield of the atomization process (LYAP). Therefore compromised consideration of quality, cost, and other related characteristics must be taken (DebRoy et al., 2018). Criteria selection and design adaptation for relevance to sustainability performance requirements is reported in this chapter.

### **4.3 Criteria selection and adaptation**

To analyze the sustainability performance of AM, the primary information one needs to categorize based on product life cycle requirements and identify criteria for evaluation. These criteria are sustainability-related and must be developed based on the life cycle requirement of products. Therefore, this approach is followed to select necessary criteria and possible way of

adaptation to selected application and summarized to life cycle stages and benefits of AM and CM processes as shown in Table 4.1.

Table 4.1 is proposed by authors based on life cycle requirements of the four life cycle stages of pre-manufacturing, manufacturing, use, and post-use for improved approaches to the overall sustainability of manufacturing through system-level thinking (Badurdeen and Jawahir, 2017; Yuan et al., 2012). Furthermore, supportive information is gathered from Table 2.1 in Chapter 2 which reported selected indicators for both AM and CM methods based on the information gathered from various literature focusing on sustainable performance. This will assist current and future researches on sustainability, especially in proposing comprehensive sustainability performance indicators and decision-making methodologies as reported in Chapters 5 and 6. Life cycle requirements considered for each stage are reported as follows.

### **1. Pre-manufacturing (design) stage:**

The lifecycle requirements included under this stage are material availability, extraction, and processing, packaging, and storage of raw materials and essential requirements of a good product design. Product-specific environmental and economic impacts are largely considered during the design stage in various parts of conventional manufacturing (Haapala et al., 2013; Shao et al., 2017; Yuan et al., 2012). A strong focus on sustainability is being given at the pre-manufacturing (design) stage for better utilization of sustainability performance indicators and according to (Sossou et al., 2018), the research efforts into the design for additive manufacturing have been mostly dedicated to part's design. These include improved quality, enhanced overall performance, minimized overall machine and machining cost, optimization of cutting conditions and related criteria, cost minimization by avoiding warranty returns and minimized defect probabilities, etc. is possible (Beaucaire et al., 2012; Duc et al., 2006; Kiswanto et al., 2014; Langeron et al., 2004; Rauch et al., 2009).

Furthermore, (Ahmad et al., 2018) mentioned that traditional product design focuses on product functionalities, quality, and cost for meeting customer requirements whereas sustainable product design (SPD) systematically views the entire product life cycle for functionality, environment, and economic performance.

### **2. Manufacturing stage:**

The life cycle requirements considered in the manufacturing stage include process inputs and outputs, infrastructure, machinery equipment & tools, warehouse & inventory, training towards health & safety, health & safety, and workers & staff. It is also mentioned (Chapter 2) requirements of sustainable manufacturing of products need to use manufacturing processes that minimize negative environmental impacts, conserve energy (by modifying the production process

that uses less material and energy inputs) and natural resources, are safe for employees, communities, and consumers and are economically sound (Ahmad et al., 2018; Moktadir et al., 2018; Shao et al., 2017). Furthermore, utilization of input materials that are renewable and nonhazardous, use more efficient transport and logistics system, design products to be reusable, re-manufacturing, recyclable, and bio-degradable, and working with stakeholders and customers to reduce the environmental impact of the industry (Moktadir et al., 2018).

In conventional manufacturing, better sustainability in conventional manufacturing is achieved through increased productivity via faster tool path, improved surface quality, material removal rate, tool life, tool geometry, and cutting conditions in milling (Kiswanto et al., 2014; Langeron et al., 2004; Prat et al., 2012; Rauch et al., 2009). However, major benefits of additive manufacturing technologies such as direct printing from CAD model, optimization, prototype manufacturing, flexibility, complexity, product customization, resource efficiency through the realization of an optimized object, operation-related issues, supply chain (Gardan and Schneider, 2015; Gebisa and Lemu, 2017; Huang et al., 2013; Jared et al., 2017; Nathan, 2015; Sossou et al., 2018; Tang et al., 2016; Thompson et al., 2016) are taken as contributing to benefits for better sustainability.

### **3. Use and post-use:**

The use and post-use stage consider life cycle requirements of the 6R concept, material resource, output waste, energy usage, emissions, functional requirements of product & user-product relationship, and quality & packaging. It is known that the use and post-use issues are major reasons to categorize manufacturing processes into traditional, lean, green, and sustainable manufacturing (Badurdeen and Jawahir, 2017). Considering the use and post-use stages, targeting sustainability through design products to be reusable, re-manufacturing, recyclable and bio-degradable as well as working with stakeholders and customers to reduce the environmental impact of the industry is most beneficial (Moktadir et al., 2018) for better sustainability.

### **4. Logistics:**

The logistics stage considers life cycle requirements of emissions & associated sustainability impact and location of shop floor & site for end-of-life operations. Similarly, it is recommended using a more efficient transport and logistics system as reported by (Moktadir et al., 2018) is more beneficial for better sustainability performance.

Thus, based on the information about LC requirements mentioned for each stage, a detailed description and possible benefits of AM over CM are developed as described in Table 4.1.

Table 4.1 Life cycle stages and benefits of AM over CM processes

LC stages	LC requirements	Description	Benefits of AM over CM
		What does each LCR mean concerning processing?	What are the benefits gained by AM as compared to CM process?
Pre-manufacturing	Material availability, extraction, and processing.	Efficient utilization of available renewable materials with maximized sustainability performance (minimum embodied energy, minimized energy consumption associated with extraction and processing) and applying end-of-life value recovery options.	CM involves cutting and removal of material to achieve the necessary shape but in AM, wasted material is reduced. Thus, the better efficiency of the material is characterized by AM.  CM produces lots of waste which has to be recycled as compared to AM which, the only material consumed in AM is the material that is needed to build the part. This makes AM more convenient for recycling.
	Packaging & storage of raw materials	Standard operating procedures and requirements of storing raw materials.	AM reduces the number of references of materials since only one powder is required by the material.
	Essential requirements of a good product design.	Material and energy-efficient products and processes associated with energy-saving for increased overall product efficiency, functionality, safety, usability, and economic feasibility.	AM shows a better opportunity of minimizing material waste and also has better chances of minimizing energy needed for transportation.
Manufacturing	Process inputs and outputs	Efficient use of production process inputs such as material, energy, and water. The amount of material used for the part and support, utilization of clean, renewable and low energy content materials are also considerations to be made.	AM makes it possible to integrate many functions into a one-piece part. AM uses the same facilities to produce, modify and repair parts.
		Management of process outputs such as emissions, effluents, and waste. Quality, destination, and impact of process outputs and effect on the ecosystem and human health.	The effect of EEW is connected with machines utilized, transportation, and mechanism of disposal.
	Infrastructure, machinery equipment & tools	Economic values of machinery used for manufacturing, assembly, finishing, handling of tools and machines, and shop floor automation.	Additional costs associated with creating complex products are eliminated by using AM.  Encourages entrepreneurship and product development by minimizing barriers due to the ease of producing a prototype just by printing in one machine rather than requiring a factor setup.
		Overall operating, associated costs, environmental protection expenditures, and similar investments on assembly, disassembly, finishing, post-processing, and treatments, etc.	AM makes production high-value parts that can't be produced by CM with a single initial cost within a limited list of equipment and space.
		Energy consumption and efficiency of machines, transport facilities, feedstock, and powder preparation processes.	Better efficiency in AM than in CM in energy consumption in transportation.



Use and post-use	Warehouse & Inventory	Raw materials and finished products are available in the warehouse for sustainability.	Easily available for AM.
		Clean and organized warehouse without spills, harmful chemicals, adverse working conditions which ensures safety and comfort.	AM finds better opportunities over CM.
	Training towards health & safety	Proper training of employees on material handling equipment, health, and safety to operate equipment with better operational safety and to minimize workplace injury rate.	Can easily be done for AM than CM.
	Health & safety	Minimization of waste and emissions, proper management of pollutant and waste effects due to lack of proper ventilation, disposal system, risk minimization with the integration of fire hazard and medical emergency services	There is a variation among the two processes for compliance to social standards. The injury rate is significantly minimized as there is no continuous contact of workers while manufacturing. On the other hand, the handling of powders can be very dangerous for the health of personnel. Different types of social standards are set but compliance depends on the type of process used.
	Workers & staff	Performance, efficiency, productivity, and continuous improvement of employees will be affected by lack of safety tools, leisure facilities, wage levels, etc. Thus, proper training and education combined with other key factors will be used as strategies to help fulfill requirements for workers and staff.	The type of process will have an impact on the type and required performance of manpower as an employee. AM requires a complete reconfiguration of the skill set needed to design and manufacture new products.
	The 6R concept	End-of-life processing strategies are based on the 6R principle to minimize the overall product's impact.	Better implemented in AM than in CM.
	Material resource, output waste, energy usage, emissions	A shift towards a closed-loop system where minimization of material and energy inputs for product function and consumer demand is taken into consideration. Minimization or elimination of adverse impacts of waste and emissions is also considered.	A high level of design freedom and flexibility in AM allows better performance for it than CM.
	Functional requirements of product & user-product relationship	Quality of product (rigidity, durability, and required mechanical property) and necessity of post-processing activities to improve overall properties up to performance or customer requirements.	AM helps to produce customized or parts with multiple integrated components for better commercial benefit. It helps to create personalized products by just using 3D printers to test the customized products. Besides, it is a high level of customization for conformity as per the demand of the customer.
	Quality & packaging	Perspectives of customer satisfaction, public trust, and product reputation. This can start from planning to mitigate the environmental impact and extent of	There is a trend of reducing or avoiding packaging for the sake of safety during transportation since AM makes the possibility of manufacturing the product just at the place where users can get it.

Logistics		PSS. It includes initiatives of energy-saving, value addition to products, and recycling strategies.	
	Emissions & associated sustainability impact	Transportation of raw material from extraction to the processing station and then to manufacturing shop.	Manufacturing can be closer to users and can easily be built locally rather than in large factories.
		Emission associated with the transportation of products from the manufacturing station to users and reverse transportation of products for end-of-life operations after service.	AM saves time as it is easy to get into the market without wasting time on retooling or logistics aspects. CAD file will be enough to accommodate modifications within few hours of the request.
	Location of shop floor & site for end-of-life operations	Plant's location concerning design and production department and customer location for minimized environmental impact through implementation and strategies of energy-efficient modes of logistics.	A 3D printing device can be implemented locally and make manufacturing closer to users of products which significantly shortens supply chains and cuts down logistics and transportation costs in CM.

The main purpose of proposing Table 4.1 is to relate product life cycle requirements with the possible benefits of additive manufacturing over conventional manufacturing processes. For each stage of PLC, details of the meaning of each LC and how each requirement is related to processing. Finally, the benefits gained by AM as compared to CM are highlighted. In the description column, it can be observed that design adaptations for AM should first target manufacturing by avoiding support because it is related to the amount of material consumption and also the powder has an impact on human health. Design adaptation needs towards AM are explained in section 4.4.

#### 4.4 Design adaptation requirements to AM

It already mentioned that research efforts into the *design for additive manufacturing* (DfAM) have been mostly dedicated to part's design, which is a requirement for a better industrial adoption (Sossou et al., 2018). Since AM is capable of manufacturing fully functional assemblies requiring a few or no assembly operations, there is a need for DfAM methodologies tackling product developments more holistically, and which are, therefore dedicated to assembly design. Design modification or adaptation is mainly required when parts are designed for additive manufacturing. Thus, for better adaptation, it is necessary to know the limitations of AM and understand the requirements of today's DfAM process. For example, Figure 4.1 shows today's state-of-the-art DfAM process where eleven steps are represented in three categories of component design, part design, and process design. The process begins choosing components for AM until verification of AM capability through manufacturing and preparation of the part for the manufacturing and post-processing. Arrows back to earlier steps illustrate an iterative process, which despite the chronological design process is a necessity.

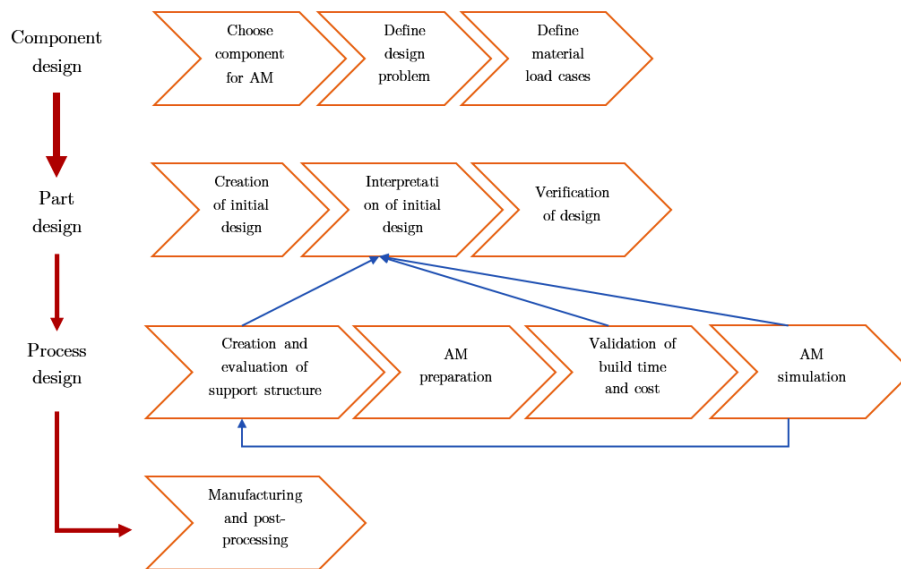


Figure 4.1 State-of-the-art DfAM process (Wiberg et al., 2019).

The relevance of Figure 4.1 to sustainability is to exploit opportunities of AM by going through each step of the DfAM process with a focus on criteria that favor AM in a design process. These include design rules, materials used, machine type, and setting. In AM, setting up of manufacturing highly influences the part that is manufactured and also depends strongly on related parameters where the effect on change on one parameter is reflected on the other. These settings can be categorized as energy-related, scan-related, power-related, and temperature-related. Energy-related settings include the power of the energy source, spot size, and pulse duration and frequency. Scan-related settings include scan speed, scan spacing, and scan pattern. Powder-related settings are linked to the material used and include particle shape and size, as well as how the powder is distributed and which layer thickness is used. Finally, temperature-related parameters include the temperature of the powder bed, feeder, and the uniformity of the temperature (Wiberg et al., 2019).

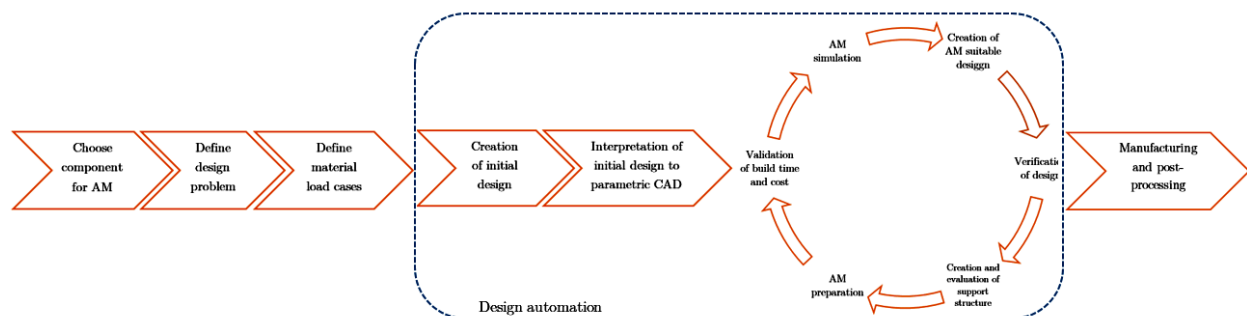


Figure 4.2 Design automation framework (Wiberg et al., 2019).

Figure 4.2 shows a newly proposed type of design process for additive manufacturing by (Wiberg et al., 2019) which aims to achieve a more automated design process for AM. The framework

shows the potential for reducing the iterative work within the design process. Once the design process for additive manufacturing is identified, it is necessary to consider necessary adaptations for the selected application. This needs full awareness on the part or selected application, type and availability of input material and finally, method based on (Džugan and Novy, 2017; EPAM, 2015; Zwier and Wits, 2016).

#### **4.4.1 Part selection**

In part selection, relevant considerations to make are part size, wall thickness capacity of the process used, max channel diameter and length, geometrical accuracy, part density, surface quality, defects due to incorrect process parameters, build strategy, part orientation, and insufficient powder quality, support, etc. part density and surface quality are affected by overhang angle.

According to (EPAM, 2015), considerations of part size, property, and post-processing must be taken into consideration. In the case of powder bed technologies, the part size is limited to power bed size (250×250×205 mm) and this is one limitation set for additive manufacturing. AM is suitable for small or unitary series (25000 parts per year) not relevant for mass production. Moreover, parts manufactured by AM tend to show anisotropy in the construction or built direction and even though densities of 99.9% can be reached, there can still be some residual internal porosities. The scanning pattern will influence porosity level, microstructure, surface roughness, and heat buildup in the finished metal components. The need for post-processing activities includes machining, electron discharge machining (EDM), peening, grinding, polishing, surface treatment, heat treatment, hot isostatic pressing (HIP) to eliminate residual porosity, control.

#### **4.4.2 Input materials**

The other relevant information needed is knowledge about the main input materials. The main input materials are metal powders and wires. Wires are significantly cheaper than powders. The offer of feedstock alloys available in the form of wires is significantly wider. Powder-based technologies can use special materials not available in the bulk form - advantage. Powders are made either by water or gas atomization. Typical characteristics such as shape, size distribution, surface morphology, composition, and flowability of the powders (DebRoy et al., 2018; Džugan and Novy, 2017; Zwier and Wits, 2016). The type, property, size, and powder characteristics of input materials are highly relevant for design adaptation. Concerning powder size, laser powder bed fusion will fabricate a part by spreading a thin layer of powder (20 to 100 µm) across a build platform using a high power laser to selectively melt regions of that layer. Moreover, information concerning powder depends on metal powder characteristics and size. For characteristics,

chemical composition will affect melting temperature, mechanical property, weldability, thermal property, etc. and the following material-related issues should be considered.

- Particle size distribution affects powder flowability or spreading, powder bed density, energy input needed to melt the powder grains, surface roughness, etc.)
- Rheological properties (density, flow rate, angle of repose, etc.)
- Storage and aging of powders
- Reusability of powder after AM cycles
- Health, safety, and environmental issues.

#### 4.4.3 Manufacturing processes

According to (EPAM, 2015), two broad methods of manufacturing processes can be considered as powder bed technology (PBT) and blown powder technology (BPT), where PBT is categorized as laser beam melting, electron beam melting and 3D printing or inkjet printing. This classification is represented in Figure 4.3. In this method, the powder layer is first applied on a building platform and then the electron or laser beam will selectively melt the upper layer of the powder. After melting, the platform is lowered and the cycle is repeated until the part is fully built. The system contains a powder feeder, laser source, recoater (roller or blade), and building platform.

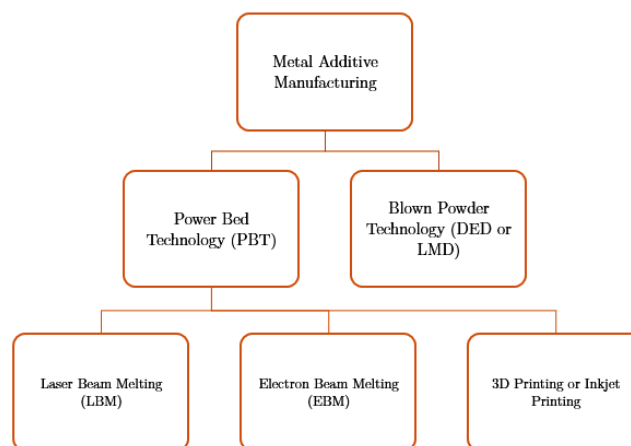


Figure 4.3 Mapping of main metal powder additive manufacturing technologies (EPAM, 2015)

In methods selection and utilization, important factors include scanning patterns, post-processing activities, build strategy and orientation, available surface roughness, etc. Design rules for Laser beam melting (LBM) or Selective Laser Melting (SLM) include consideration of minimum wall thickness, minimum hole diameter, maximum arch radius, maximum channel diameter or length, minimum strut diameter, minimum gap distance, reproducibility, geometrical accuracy, and surface roughness. Self-supporting design for additive manufacturing is identified by calculating and understand overhang angle, which is the angle between the build platform and the part. As represented in Figure 4.4, when the angle between the part and the built platform is less than

or equal to  $45^\circ$ , no support structures are needed otherwise to void poor surface roughness as well as distortion and warping leading to build failure, support is needed (EPAM, 2015; Fox et al., 2016; Zwier and Wits, 2016).

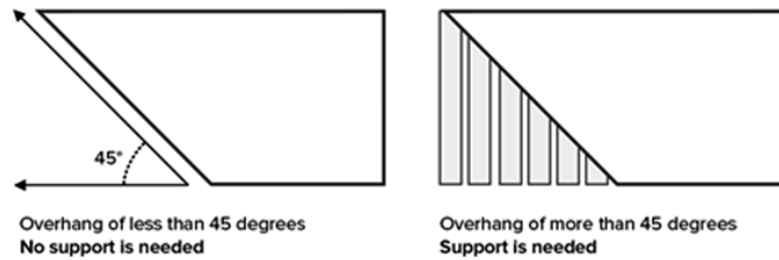


Figure 4.4 Representation of overhang angle

The other important parameter is the heat accumulated during the build of thin-walled structures. This increases the surface roughness through an increase in adherence of partially melted powder particles to the part surface. Process inputs contributing roughness include beam power, beam velocity, and overhang angle and their relationship with surface characteristics and surface roughness parameters (Fox et al., 2016).

#### 4.5 Capabilities of AM for better sustainability

This section presents different capabilities of additive manufacturing processes for better sustainability performance as compared to conventional manufacturing processes. These capabilities are identified with justification and proper citation to further contribute to the development of sustainability performance indicators reported in Chapter 5.

*Design freedom:* AM can produce components with fewer design restrictions that are common challenges of the traditional manufacturing processes.

*Part consolidation:* Produce monolithic structures with improved performance (indicators) or the possibility of part consolidation. Parts that are produced by AM must meet levels of performance established by traditional manufacturing processes (Vaneke, 2017).

*Complex geometries:* Shape complexity, material complexity manufacturing of complex structures which are difficult for conventional manufacturing (example, casting or machining). In AM, complexity is for free which means that complex geometries are no more issues of design engineers (Gebisa and Lemu, 2017; Vaneke, 2017). Besides building complex geometries, it helps to build hierarchical structured parts, multi-material in a single part manufacturing and functionally integrated objects. Moreover, it produces parts with complex designs that can overcome the need for multiple parts.

*Product customization:* Customized fabrication of tools: BMW used AM in direct manufacturing to make the hand tools used in testing and assembly with better ergonomic design and 72%

lighter weight than traditional hand tools. It is reported that it resulted in overall cost reduction (58%) and reduction in project time (82%)(Vaneke, 2017).

*Enhanced functionality:* It can add improved functionalities such as integrated electrical wiring (through hollow structures), lower weight (through lattice structures), and complex geometries that are not possible through traditional processes. Moreover, new AM technologies are producing multi-material printed parts with individual properties such as variable strength and electrical conductivity. These AM processes are hopes of future vehicles which are faster, safer, lighter, and more efficient (Giffi et al., 2014).

*Minimized lead time:* It is also considered as a driver for supply chain transformation by minimizing the overall lead time, thus improves market responsiveness. However, conventional machining needs either adjustment or tool change for every design change, which is a time-consuming and costly process. Shorten the development phase of the product life cycle. Direct part production also helps to minimize lead time and has been made possible by increasing material quality from AM processes, decreasing cost, and growing awareness of the potential of additive processes (Giffi et al., 2014; Gupta et al., 2012; Vaneke, 2017).

*Cost minimization:* It reduces the capital required to achieve economies of scale and it increases flexibility and reduces the capital required to achieve scope. Moreover, lightweight products can minimize handling costs and also tooling costs in product design. Cost minimization is possible through reducing assembly and production costs through part simplification, product customization, reducing time to market, flexibility in product development, complexity for free, part consolidation, and efficient use of materials. To mention some applications, current automakers used AM to prepare tooling and investment castings for every design. FORD saved millions of dollars in product development costs (cylinder heads, intake manifolds, and air vents) by using AM to create prototypes and skipping the need for tooling. Example: for Engine manifold, developing and creating a prototype used to take 500,000USD and four months but by using AM, Ford develops multiple iterations of the component in just four days for 3,000 USD (Giffi et al., 2014; Vaneke, 2017).

*Accelerated product design phase:* AM helps to accelerate the product design phase of new product development. Before deciding on new product development, companies go through several iterations. One of the advantages of AM is it can produce multiple variations of a product with little additional cost. It helps auto companies to improve their designs with the support of physical models.

*Quality:* Enhance quality via rapid prototyping and the ability to test quality ahead of actual production by automakers. See efforts by Dana and GE in the ‘application’ section.



*Weight reduction:* One of the important performance measures in engineering applications, especially in vehicles is improving fuel efficiency and giving more value to users. This is possible through AM because it has the potential of producing components with a lower weight. Weight reduction is usually taken as a measure for improving fuel efficiency and at the same time is considered as a means for efficient use of materials. Light weighting can be possible through creating a lattice structure, comprised of trusses and scaffoldings, for the interior part of a part (Gupta et al., 2012). Less material will significantly reduce costs, processing less material requires less build time, resulting in higher throughput. Example: the 2015 Ford F-150 (the entire Aluminum body is utilized and cuts the weight by around 317 Kg). The ability of AM to create complicated configurations plays an important role in reducing the weight of parts using lattice structures without compromising structural strength (Giffi et al., 2014; Gupta et al., 2012; Vaneker, 2017).

*Maintenance and repair:* AM can be used in the maintenance and repair of automotive parts such as drivetrain or engine components that may be expensive to replace when they wear out. Thus repairing can be done using AM method called Laser Metal Deposition (LMD) (Giffi et al., 2014; Gupta et al., 2012). This can be done to products when parts are expensive to replace when they wear out, long lead time or expense is associated with procurement of new parts when traditional maintenance or repair is not good to replace worn or damaged parts.

*Energy consumption:* By considering some components produced by AM in the US and compared the cradle-to-gate energy and GHG emission footprints with the case of CM in an analytically consistent manner. The life cycle inventory analysis of cradle-to-gate energy use showed that producing AM components might use 33-50% less energy than producing them via CM (conventional Manufacturing) and cumulative emission reduction potentials of CO<sub>2</sub> is 93-217 million tons of the aerospace industry through 2050 (Jin et al., 2017).

*Optimization:* A study by (Gardan and Schneider, 2015) reported that the use of optimization in AM is generally done in the context of optimization of the build direction, parameter optimization trades and optimization construction layers algorithm, and so on. The optimization of the quantity of material used is an important goal. Separate optimizations will be performed for the product material and the support material. Besides, since the interest of AM is to build parts or areas that can't be manufactured by conventional methods, the goal of the researches is on the quantity of the material that can be optimized. Two cases can be 'all part optimization' (inner and outer – design and non-design surface) or 'outer skin optimization (or part of it) can't be modified (due to functional / design specifications). Moreover, according to (Gebisa and Lemu, 2017), design optimization is a design process in which an objective function subjected to performance constraint is maximized or minimized iteratively by changing design variables such as part dimensions, geometries, material properties, and so on to come up with an optimal design.



Advantages of additive manufacturing are summarized as part consolidation, mass reduction, functional customization, personalization, aesthetics, and suitability for complex and customized geometries, part consolidation, and avoidance of limiting manufacturing constraints associated with traditional machining. The undermentioned unique capabilities include shape complexity, hierarchical complexity, material complexity, and functional complexity (Essink et al., 2017; Gardan and Schneider, 2015; Gebisa and Lemu, 2017; Sossou et al., 2018). These capabilities made AM push the boundaries of DfAM beyond its part's design and a bit nearer to assembly.

- *Shape complexity* - Near net-shaped, complex shape geometry or virtually any shape can be built which is not feasible with conventional manufacturing processes.
- *Hierarchical complexity* - Features of any length scale, micro-, meso-or macro scale, can be integrated into parts geometry. Features can be designed with complex shapes across multiple size scales. Internal structures can be changed (possibility of reducing mass) using cellular structures such as honeycombs, foams, and lattices). This has a direct impact on strength to weight (or stiffness to weight) ratios of the product so that excess use of materials is avoided and reduces cost.
- *Material complexity* - depending on the process, materials, and materials' property can be varied throughout the part's volume. This capability is fostering research into functionally graded materials or multi-material parts. Materials can be produced at one point, one layer, or as a combination of complex compositions of materials.
- *Functional complexity* - Full or partial functional mechanisms can be manufactured. It has the advantage of reducing part count, and reduce difficulties of the assembly process.

#### **4.6 Sustainable performance of Additive Manufacturing**

According to (Badurdeen and Jawahir, 2017; Golinska et al., 2015; Lambrecht and Thißen, 2015), manufacturing practices focused primarily on the different product life cycle (PLC) stages leading to excessive waste and landfill must consider lean manufacturing practices focusing on waste elimination and green manufacturing focusing on the 3Rs (reduce, recycle, reuse). In another perspective, value recovery from end-of-life products is achieved through the implementation of sustainable manufacturing practices using 6R (reduce, reuse, recycle, recover, redesign and remanufacture) methodology enables closed-loop, total life-cycle based material and energy flow. Furthermore, (Borchardt et al., 2011; de Pauw et al., 2014; Pigosso et al., 2010), utilized the term eco-effectiveness to industrial systems that maintain the healthy abundance of nature so that the waste of the production process and the product itself turn out to be raw materials of the new product or service (cradle to cradle for eco-effectiveness).

Consideration of tradeoffs between sustainability dimensions to implement strategies of increasing energy efficiency to become more sustainable is reported by (Jin et al., 2017; Shao et al., 2017). But (Badurdeen and Jawahir, 2017) reported that value in manufacturing is created through activities and interactions between suppliers, manufacturers, customers, and other stakeholders while in sustainable value creation, balanced consideration of the economic, environmental, and societal impacts on all stakeholders must also be taken and innovative strategies for sustainable value creation in manufacturing must be implemented.

Design considerations and integration of all aspects of sustainability in the existing CM processes were challenged by several constraints and had limitations to fully address all the three dimensions of sustainability called the TBL perspective (Boulanger, 2008; Bovea and Pérez-Belis, 2012; Jin et al., 2017; Peralta Álvarez et al., 2017) which can be achieved by systematically considering the tradeoffs among possible performance indicators. But the high level of freedom and related opportunities of AM, provide chances of avoiding some of these constraints and enhancing the overall sustainable performance of products throughout the life cycle of a product by simultaneous consideration of design (pre-manufacturing), manufacturing, use (repair, remanufacturing) and post-use stages (reuse, recycle, reclaim, reduce) (Eastwood and Haapala, 2015; Hapuwatte et al., 2016; Jayal et al., 2010; Rachuri et al., 2011; Tang et al., 2016). Furthermore, renowned companies such as GE, BMW, Ford, and AIRBUS, are highly investing to implement AM for prototyping test models of components, make hand tools, make lightweight versions of existing components and other complex and customized parts (Giffi et al., 2014; STELIA Aerospace, 2018). These companies benefited from better ergonomic and lightweight hand tools, used AM for prototyping to skip the need for tooling, lightweight versions of their existing components, etc.

There has been an emerging shift from DfM to DfAM due to the development of new materials, improved design methods, and societal demand (Gebisa and Lemu, 2017). AM process is among the emerging manufacturing processes that are attracting manufacturers for its promising advantage of addressing sustainable manufacturing issues than many CM processes. Better sustainable performance through weight and cost reduction, minimized the negative environmental and social impact, especially when there are high complexity and customization of parts. It also enables the design and production of multi-material, multifunctional, monolithic, and customized parts that are indirectly related to our resource consumption and subsequent environmental, economic, and societal impact. According to (Frazier, 2014), AM is believed to minimize negative environmental impact through efficient resource utilization and recommended that a systems approach that spans the cradle to grave life cycle of AM fabricated is needed to capture the true benefits and possible pitfalls of using AM. Thus, based on these facts and literature survey assessment in Chapter 2, Table 4.2 proposed by this study. It proposes selection factors for manufacturing process and suggests relevance for the major dimensions of

sustainability. It should be noted that relative relevance and sustainability performance is considered for additive manufacturing processes when compared to conventional manufacturing processes.

Table 4.2 reported several opportunities of additive manufacturing processes over conventional manufacturing processes for better sustainability performance based on the three dimensions. However, limitations associated with AM such as poor surface finish (cause for extended post-processing activities), less production volume and building speed (the reason for low productivity), dimensional stability, uncertainty in final part mechanical properties, expensive AM equipment and material, the impact of powder on human health, etc. are also identified. The post-processing activities are used to improve the microstructure, reduce porosity and to finish surfaces, reduce roughness and meet geometric tolerance. But several strategies are also being implemented to minimize these challenges. (Bikas et al., 2016; Bourell et al., 2017; Frazier, 2014; Giffi et al., 2014; Gupta et al., 2012; Hapuwatte et al., 2016; Huang et al., 2013; Sossou et al., 2018; Vaneker, 2017; Yang and Zhao, 2015).

Table 4.2 Sustainable performance of additive manufacturing comparatively  
to conventional manufacturing processes

Selection factors for a manufacturing process	Relevance and sustainable performance						Limit ations
	Relevance			Sustainability			
	avoid	enhance	not applicable	EN	EC	SO	
Assembly cost	×				×		
Assembly time			×		×	×	
Build to order strategy		×			×	×	
Complex features formation		×			×		
Coolant			×	×	×	×	
Cutting tools			×		×		
Design flexibility		×			×		
Efficiency of raw material utilization		×		×	×		
Embedded object manufacturing		×			×		
Emission	×			×	×	×	
Fluid spills			×	×	×		
Hazard or risk during manufacturing	×				×	×	
Health risk to employee		×			×	×	×
Jigs and fixtures			×	×	×		
Just-in-time manufacturing		×			×	×	
Lead time		×					
Machine cost		×			×		×
Manufacturing constraints	×				×		
Material (waste) generation			×	×	×		
Material consumption	×			×	×		
Monolithic structures		×			×		
Noise			×	×		×	

Occupational hazard	×			×	
Optimization flexibility & capability		×		×	
Optimized design realization		×		×	
Post-processing activities		×		×	×
Production speed	×			×	×
Productivity		×		×	×
Raw material cost		×	×	×	×
Product-specific tool requirement			×	×	×
Resource efficiency		×	×		
Responsiveness		×		×	
Setup time			×	×	×
Surface finish	×			×	×
Transportation cost	×			×	×
Transportation requirement	×			×	×
Warehousing				×	
Waste elimination		×	×	×	×
Waste reuse			×	×	×

In conclusion, it found out that based on relevance for sustainable performance, additive manufacturing processes dominated conventional manufacturing processes according to the identified selection factors for a manufacturing process. Thus, according to the majority of these factors, there is an avoidance of the negative impacts and enhancement of positive sustainability impacts. Furthermore, through the implementation of different strategies to minimize limitations or challenges noted on six of the identified selection factors, a better sustainability performance for additive manufacturing can be achieved.

#### 4.7 Conclusion

This chapter focused on analyzing the sustainability performance of additive manufacturing. This analysis was based on the benefits of additive manufacturing over conventional manufacturing through relevant sustainability criteria and opportunities for easy design adaptation to the intended product. It is mentioned that instead of removing materials, AM builds layer upon layer to build 3D objects, which minimizes waste. It helps to develop highly optimized, more intricate valuable engineering products with minimized weight and resource consumption regardless of manufacturing constraints, which are huge barriers of manufacturing in conventional methods.

Design for additive manufacturing is addressing manufacturing constraints to manufacture optimized designs which help to reduce manufacturing cost by improving product quality. This gives better opportunities to use new materials, develop improved designs as per the economic, environmental, and societal expectations for the development of sustainable products. This opportunity of AM can be expressed through the potential of producing complex shapes, near

net shaped fabrications, consolidated parts, multifunctional, lightweight, and associated opportunities of energy savings from transportation, assembly, and waste less manufacturing.

The benefit of AM over CM is also analyzed from a product life cycle perspective. This life cycle category considered pre-manufacturing (material selection and design aspects), manufacturing, use, and post-use activities and logistics. Each of these life cycle stages is further associated with requirements. The scope of life cycle requirements can be further elaborated by designers depending on the considerations made. The main intent of this study was to find opportunities of AM throughout the PLC and it is found out that better opportunities inefficient utilization of resources, cost minimization with part complications, economic values of machinery needed for investment, assembly, tool handling, and shop floor automation, warehouse, training of employees, waste minimization, performance improvement of employees, end of life processing strategies, customer satisfaction, and public trust, transportation, location advantage, are major opportunities identified in AM as compared to CM processes.

Understanding each step of the DfAM process passes through three steps; component design, part design, and process design. Design adaptations for AM through each step of the DfAM process considers opportunities and suitability to AM. For design adaptation needs, considerations about part selection, input materials, and method of manufacturing are highly relevant. For example, about a part, minimum considerations of size, property, post-processing requirements must be taken into considerations depending on the type of AM technology. Moreover, knowledge about input materials, whether powder or wire, must be assessed from cost, type, property, shape, size, surface morphology, composition, and flowability. Finally, selection of AM methods relevant information about part size requirements, energy source, scanning pattern, post-processing activities, build strategy & orientation and available surface roughness are relevant to consider.

Opportunities of AM for sustainable performance are proposed based on its unique capabilities of assuring sustainability when compared to CM processes. These are categorized as shape, hierarchical, material, and functional complexity. Based on these opportunities relevance of AM for better sustainability performance is evaluated in the following factors for a manufacturing process; minimized assembly cost, build to order strategy, complex feature formation, design flexibility, efficient utilization of materials, embedded object manufacturing, minimized emission, minimized health risk (no powder for support), just-in-time manufacturing, minimized lead time, minimized (no) constraints, minimized material consumption, the capability of manufacturing monolithic structures, minimized occupational hazard, the realization of optimized designs, better responsiveness, minimized transportation requirement (cost), and a high chance of waste elimination. Therefore, manufacturability with minimized constraint for better sustainable performance can easily be achieved by understanding criteria selection and design adaptation requirements to fully exploit opportunities of Additive Manufacturing.

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## Chapter 5

### Sustainability Performance Indicators

#### 5.1 Introduction

To select indicators among the list and develop an exhaustive list of sustainability performance indicators, understanding the current status of sustainability, sustainable performance, and associated performance indicators is necessary. This has been done through intensive literature assessment so that a new, comprehensive list of sustainable performance indicators (SPI) is proposed and interpreted.

The current challenge in the identification and utilization of sustainable performance indicators (SPIs) and convenient manufacturing processes mainly due to the lack of standardization and detailed descriptions and measuring strategies. Therefore, identifying, categorizing, and describing an exhaustive list of performance indicators (PIs) and measuring strategies is expected to assist designers, manufacturers, decision-makers, and users to easily choose alternatives to model their problems towards sustainability to categorize, describe and propose a new comprehensive list of SPIs based on product life cycle (PLC) perspective. Doing this can serve as a reference to evaluate alternatives, policy choices, quantifying and benchmarking the sustainable performance of products' design and manufacturing processes. Furthermore, results can be used as key input towards introducing a standard to set universally accepted SPIs and measuring strategies targeting additive manufacturing (AM). A top-down approach of identifying sustainability into the environment, economic and social dimensions is utilized. Furthermore, considerations of PLC, an exhaustive analysis of social aspects, and the calculability of identified indicators are properly addressed.

Therefore, this chapter proposes a new framework of sustainability performance indicators by considering gaps identified on current understandings on sustainability, sustainability dimensions, and associated performance indicators as well as opportunities for growing trends in design and manufacturing. Development of this framework is done by harmonizing current understandings and requirements of future needs of the manufacturing system based on globalization and increasing demands on sustainable products, environmental and social responsibility concerns.

#### 5.2 Current understandings and gaps

From the literature survey reported in Chapter 2, it is well understood that the scientific community faced various subjective understandings on sustainability and approaches to measure it, consideration of sustainability dimensions, and associated performance indicators. Assuring

sustainability is also changing based on the current trends in product design and manufacturing. Though these subjective understandings and gaps are limited to the goal or scope of the study assessed, there are growing and encouraging trends that are used as input in proposing the new list of SPI. Therefore, key findings on current understandings on sustainability, sustainability dimensions and associated performance indicators and opportunities of current trends in design and manufacturing for sustainable performance and gaps specifically relevant to propose sustainability performance indicators in section 5.3.

### **5.2.1 Sustainability**

According to the current research outcomes, the main challenges in manufacturing industries are subjective understandings of sustainability and unbalanced and incomplete consideration of performance indicators. Moreover, incomplete coverage of sustainability dimensions throughout the product life cycle is another challenge observed in evaluating sustainability. Even though there is growing research considering all dimensions of sustainability, a study by (Moldavska and Welo, 2017; Peralta Álvarez et al., 2017) showed that past researches focusing on sustainability were based on considering environmental dimension than social dimensions or more precisely considering it as environmental initiative or perspective. The current most convincing understanding falls on analyzing both the environmental performance and socio-economic considerations of manufacturing processes and systems throughout the product life cycle.

The current sustainable performance measurement of manufacturing depends on such subjective understandings on researchers. But since sustainable design and manufacturing became the research focus of engineers and scientists, as well as an increasing trend in the demand for more sustainable products from users through better concerns to the environment and social impacts, and enhance effort is being put to work on true measurements. Moreover, according to (Gupta et al., 2016; Moldavska and Welo, 2017), sustainable manufacturing is considered as one of the measures towards sustainable development after it is set as one of the sustainable development goals set by the United Nations.

Moreover, According to (Haapala et al., 2013), mass production, globalization, increasing demand for sustainable products, ecological concerns, and social responsibility are key issues in the current manufacturing system. Even though subjective understandings on the sustainability of manufacturing widely observed, accepted by the United States Department of Commerce, a more sound definition of sustainable manufacturing consider it as the creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, consumers and are economically sound through value recovery from end-of-life products (Badurdeen and Jawahir, 2017; Kulatunga et

al., 2015; Li and Mathiyazhagan, 2018; Moktadir et al., 2018; Pigosso et al., 2010; Shao et al., 2017).

A highly compelling factor for industries to assure sustainability and keep them highly competent and reputable on the current market is the recent increase in awareness for sustainable products and their impacts of design and manufacturing of products associated with resource consumption, pollution, safety, and risk on human and ecosystem, durability, performance and overall life cycle cost (Ahmad et al., 2018; Ceschin and Gaziulusoy, 2016; Eastwood and Haapala, 2015; Madan Shankar et al., 2017; Zhang et al., 2013).

The report that 80% of sustainability impacts are decided at the design stage, led researchers to focus on the manufacturing sector which can realize any design and propose a strategy for sustainability and cleaner production objectives. For instance in various practices of conventional manufacturing (CM) processes, product-specific environmental and economic impacts are largely considered during the design stage (Haapala et al., 2013; Shao et al., 2017; Yuan et al., 2012). This stage took most of the attentions of researchers focusing on sustainability since better utilization of performance indicators (PIs) such as improved quality, enhanced overall performance, minimized overall machine and machining cost, optimization of cutting conditions and related criteria, cost minimization by avoiding warranty returns and minimized defect probabilities, etc. is possible. (Beaucaire et al., 2012; Duc et al., 2006; Kiswanto et al., 2014; Langeron et al., 2004; Rauch et al., 2009). Now, there is an emerging shift towards design for AM from design for manufacturing, in which its sustainability performance needs to be properly evaluated.

### **5.2.2 Sustainability dimensions and indicators**

The understanding of sustainability and sustainable manufacturing will help in identifying and selecting necessary performance indicators for sustainability evaluation. Sustainability won't be fully achieved without a complete and balanced understanding of indicators from each dimension. It is found out that the most meaningful sustainability framework is based on the triple bottom line (TBL) approach as reported by (Peralta Álvarez et al., 2017). The increasing growth and global competitiveness in product design and development require consideration of appropriate performance indicators for sustainability evaluation.

It is understood that recent works of literature have tried to address issues of sustainability, mainly in CM processes, in various contexts and applications but none were able to propose comprehensive frameworks and strategies to address it fully. One key issue is the lack of exhaustive consideration of performance indicators (PIs) throughout the PLC. For example, (Reich-Weiser et al., 2008) tried to develop PIs focused on energy use, climate change, and non-renewable resource consumption. But social dimension is entirely missing and there are still

unconsidered yet vital sustainability indicators that fully characterize sustainable manufacturing. On the taxonomy of eco-design tools for integrating environmental requirements into the product design process, (Bovea and Pérez-Belis, 2012; Karlsson and Luttrupp, 2006) reported that besides environmental requirements, what they called “traditional requirements”, legal, economic, functional, health, and safety must be taken into account.

Methodologies and sustainability frameworks in environmental, or in a wider scope of sustainable design, didn't fully provide a comprehensive framework for identification of the relevant improvement strategies through consideration of indicators related to part or product characteristics (Bereketli and Erol Genevois, 2013; Brones and Monteiro de Carvalho, 2015; Dufrene et al., 2013). In identifying indicators during sustainability evaluation of product development needs proper understanding of the method (new product design, improvement of product or process), life cycle stages (pre-manufacturing, manufacturing, use, and post-use), point of application (classification of the task, conceptual, embodiment and detail design, production planning), sustainability dimensions (TBL), type of processed data (qualitative, quantitative or semi-quantitative), the method user (product manager, designer, production planner or user), abstraction layer (product, process, requirement, component, service) (Buchert et al., 2014).

The incomplete and subjective consideration of performance indicators is a primary motivation to develop simple, complete, and high-level performance indicators which can be compared to standards for various applications (Ahmad et al., 2018; Cohen et al., 2014; Rachuri et al., 2011). Because most of the PIs currently identified are more focused on evaluating environmental performance (Ahmad et al., 2018; Buchert et al., 2014; Rossi et al., 2016; Yuan et al., 2012) than considering complete sustainability indicators (Jain, 2005) and also as per many of the sustainability guidelines cited by authors such as (GRI, 2000), it is important to have a comprehensive understanding and balanced consideration of all PIs for measuring all dimensions throughout the life cycle of the product (Ahmad et al., 2018; Eastwood and Haapala, 2015; Haapala et al., 2013; Joung et al., 2013; Shao et al., 2017; Yuan et al., 2012). Thus, further work is needed to exhaustively identify and propose a full list and description of SPIs. Proper categorization and quantification of these indicators are required to establish further decision making frameworks or strategies, as it gives better opportunities towards overall sustainability measurement.

### **5.2.3 Trends in design and manufacturing**

The proposal of sustainability performance indicators is based on understanding opportunities of trends in the current design and manufacturing and how to associate this trend to dimensions of sustainability. Thus, it is necessary to understand how to fetch relevant information to propose sustainability performance indicators. A more comprehensive description of sustainable design

and manufacturing is given by (Moktadir et al., 2018) that concerns utilization of renewable, fewer materials, and inputs that are not hazardous, modify production process that uses fewer materials and energy, use more efficient transport and logistics system, design products to be reusable, re-manufacturing, recyclable and bio-degradable and working with stakeholders and customers to reduce the environmental impact of the industry. This agrees with requirements of product creation using minimum economic and environmental impacts that are safe for employees, consumers.

Therefore, to achieve goals of sustainable manufacturing and measurement, it is highly recommended to focus on manufacturing processes and equipment, manufacturing systems, changes in life cycle paradigms, and education. Categorizing manufacturing as AM and CM and separately identifying opportunities of AM is helpful for better consideration of sustainability requirements for different life cycle stages. The shift towards design for AM (DfAM) enables improved sustainability performance through minimized resource consumption to give a better environmental performance through reduction in weight and cost as well as minimized economic and social impact.

Finally, considerations on more case studies, overlooking design stages, and utilization of more data and metrics are needed to further assure sustainability. Engineers utilize different methodologies from simple checklists to sophisticated analytical tools to support product development. Due to these concepts, it was recommended as further work is necessary based on system-level thinking to exhaustive identification, quantification, and generation full list and description of sustainable performance indicators. Development of these performance indicators will be done based on exhaustive requirements of the development of sustainable products and growing trends in design and manufacturing via the three dimensions of sustainability to minimize negative environmental and social impacts by simultaneously maximizing economic benefits.

### **5.3 Proposed sustainability performance indicators**

In this section of the study, a more comprehensive list and description of SPIs is proposed and interpreted by considering the sustainability performance of AM through extensive literature review mainly within the past decade evaluated from different contexts and applications throughout the PCL. Researchers utilized a top-down approach to establishing this list of PIs as represented in Figure 5.1. A full description of each category of sustainability is reported in sections 5.3.1 to 5.3.3. In proposing these SPI, it is also considered how categorization and evaluation are done depending on the type of available parameters.

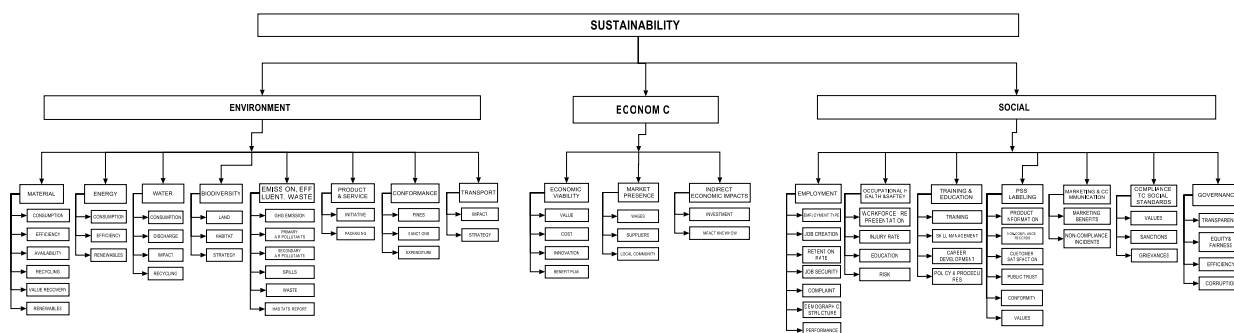


Figure 5.1 Proposed sustainability performance indicators

Categorization and proposal of SPIs are reported based on three dimensions, environment, economic and social dimensions, as shown in Figure 5.1. Moreover, for each dimension, second and third-level categories (categories and subcategories) of these indicators are reported. The second level category considers 18 indicators (8 for the environment, 3 for economic, and 7 for social), and the third-level subcategory results in 68 indicators among which 29 are for the environment, 9 for economic, and 30 for social dimensions. Once these categories are developed, interpretation and quantification strategy whenever necessary is reported in Tables 5.1, 5.3, and 5.5.

### 5.3.1 Environment performance indicators

Resources as input and output are major sources of the environmental impact. This section reports a detailed list and interpretation of each environmental performance indicator. Thus, Figure 5.2 reports categories and subcategories of the environmental dimension of sustainability.

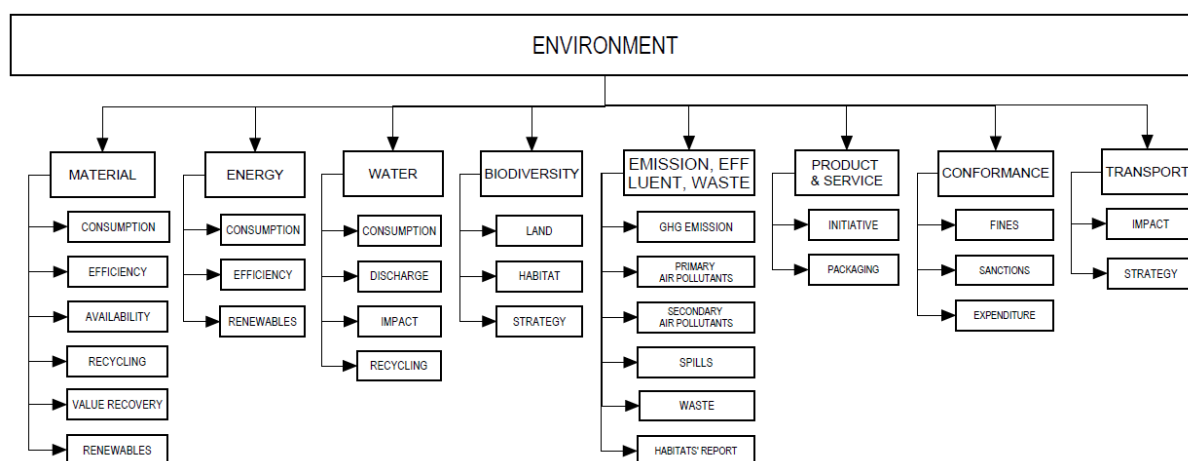


Figure 5.2 Categories and subcategories of environmental performance indicators

The following list of environmental performance indicators is proposed based on detailed analysis and assessment of the existing impact on the environment. Table 5.1 mentions each SPI for

environment dimensions, mechanism of evaluation, and what data is needed to evaluate this SPI list whenever required.

Table 5.1 Environment performance indicators

SPI	Formula (whenever required)	Data needed for SPI evaluation
MAC Material consumption	Weight/volume of material consumed by the part.	Material consumed to produce parts [Kg].
MAE Material efficiency	Material efficiency ( $\eta_m$ ) $\eta_m = \frac{M_I - \sum_{i=1}^p W_i}{M_I}$	Total material loaded into the system ( $M_I$ ) [Kg] and wasted material in all existing processes ( $W_i$ ) [Kg].
MAA material availability	It is calculated as a sustainability factor as (used/available) or the fraction of available resources consumed.	Considerations will be made on a range of necessary materials in the feedstock, general material availability for designer's choice, sets of materials suitable for the selected machine and with lower environmental impact, and a fraction of available resources consumed.
MAR material recycling	It is calculated as the amount of material recycled or the percentage of material recycled.	Is there any practice of recycling materials (partly or whole) after the end-of-life of the product? If so, what percentage? or What amount?
MAV value recovery		Available end-of-life (EoL) value recovery options such as reuse, upgradable components for refurbishing. A measure of eco-effectiveness can be used.
RMA renewable materials	Percentage of renewable materials used.	The trend of using raw materials from renewable sources for better environmental performance.
ENC energy consumption	Energy consumption ( $E_c$ ) $E_c = \sum_{j=1}^N P_j \times \eta_{opj} \times t_{opj}$	Determined from the number of facilities needed to produce the product (N), the power demand of respective facilities used to produce the product (P), the operation efficiency of the facility ( $\eta_{op}$ ), and operating time of the facility.
ENE energy efficiency	Amount of energy saved or mechanism of energy saved/avoided.	Amount of energy saved/minimized or avoided due to the new system/process.
ENR renewable energy	<i>Refer data needed</i>	Any reductions in direct or indirect energy requirements? Any use of clean energy systems to avoid possible emissions?
WAC water consumption	Water consumption [L] $H_2O_{cons} = r_w t_w$	Total amount of water consumed [L] based on water flow rate ( $r_w$ ) [ $m^3/s$ ], water flow time ( $t_w$ ) [ $m^3/s$ ]
WAD water discharge	Water discharge [L] $H_2O_{dis} = r_{wd} t_w$	Total water withdrawal during the manufacturing of the product through water discharge rate ( $r_{wd}$ ) [ $m^3/s$ ] and water flow time ( $t_w$ ) [ $m^3/s$ ]
WAI water impact		Sources of water that are impacted by the withdrawal of water.
WAR water recycled		The volume of water recycled or reused (total or percentage).



LAN land		Impact of activities on protected areas and areas of high biodiversity value outside protected areas.
HAB habitat		Habitats that are restored or protected.
BDS biodiversity		Current actions and plans for managing impacts on biodiversity.
GHG greenhouse emissions	<p>GHG emission (<math>G_{em}</math>) [kg CO<sub>2</sub> eq.]</p> <p>gas <math>G_{em} = (E_c)(r_{CO_2} + r_{CH_4} GWP_{CH_4} + r_{NO_2} GWP_{NO_2})</math></p> <p>The amount of GHG reduction (<math>G_{em}</math> [ton/\$1000]) is the cost-benefit model of using clean energy supply for GHG emission mitigation from conventional grid supply.</p> $G_{em} = \frac{(E_{local} - E_k) \times A_k \times T_k}{(C_{Nk} + C_{Vk} \times T_k + C_{Fk}) A_k}$ $G_{Product} = \sum G_{Material} + \sum G_{Use} + \sum G_{EoL}$ <p>GHG emission of material at EoL stage (<math>G_{EoL}</math>)</p> <p>GHG emission of reused, recycled, and recovered material at EoL</p> $G_{EoL} = G_{reuse,EoL} + G_{recy,EoL} + G_{reco,EoL}$ $G_{reuse,EoL} = \sum_i (G_{m,i} \times (m_{m,i} \times r_{reuse,i}))$ $G_{recy,EoL} = \sum_i (G_{m,i} \times (m_{m,i} \times r_{recy,i}))$ $G_{reco,EoL} = \sum_i (H_{reco,i} \times (m_{m,i} \times r_{reco,i})) \times C$	<p>Total energy consumption (<math>E_c</math>), generation rates (<math>r</math>) of CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>2</sub>, global warming potentials (GWP) of CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>2</sub>, and emission factor of GHG from local grid power supply (<math>E_{local}</math>) [Kg/KWh]</p> <p>Life cycle emission of clean energy (<math>E_k</math>) [kg/kwh], total installed capacity of clean energy (<math>A_k</math>) [Kwh], operational life time of clean power system (<math>T_k</math>) [hours], overnight cost of clean power system (<math>C_{Nk}</math>) [\$/KW], variable O&amp;M cost of clean power system (<math>C_{Vk}</math>) [\$/KWh], fixed O&amp;M cost of clean power system (<math>C_{Fk}</math>) [\$/KW],</p> <p>Life cycle emission of a product (<math>G_{Product}</math>), GHG emission of material (<math>G_{Material}</math>), GHG emission during the use stage (<math>G_{Use}</math>),</p> <p>GHG emission of material <math>i</math> (<math>G_{m,i}</math>), weight of material <math>i</math> (<math>m_{m,i}</math>), reuse rate of material <math>i</math> (<math>r_{reuse,i}</math>), recycle rate of material <math>i</math> (<math>r_{recy,i}</math>), material recovery rate <math>i</math> (<math>r_{reco,i}</math>), recovered heat capacity of material <math>I</math> (<math>H_{reco,i}</math>), conversion factor to one ton of steam (<math>1.5 \times 10^{-9}</math>).</p>
PAP primary air pollutants	<p>Calculated as pollutant emission during onsite energy consumption (<math>POL_{em}</math>)</p> $POL_{em} = (EC_{onsite})(r_{NO_x} + r_{SO_x})$	<p>Determined based on onsite energy consumption (<math>EC_{onsite}</math>) [KWh], NO<sub>x</sub> generation rate (<math>r_{NO_x}</math>) and SO<sub>x</sub> generation rate (<math>r_{SO_x}</math>).</p>
SAP secondary air pollutants		Smog formed from coal-burning and SO <sub>2</sub> , Ozone formed and associated pollutants resulting from NO <sub>x</sub> and VOCs.
SPI spills		Number and volume of spills which will affect the ecosystem and human health.
WAS waste	<p>Calculated as the weight of hazardous (<math>W_{haz}</math>), landfilled (<math>W_{landfill}</math>), and recycled (<math>W_{recy}</math>).</p>	<p>The volume of hazardous waste (<math>V_{haz}</math>), the density of hazardous waste (<math>\rho_{haz}</math>), process time (<math>t_p</math>), the time between tank refills (<math>t_{ref}</math>), fraction of waste to landfill</p>

$W_{haz} = \sum_i^n \left( V_{haz} \rho_{haz} \left( \frac{t_p}{t_{ref}} \right) \right)_i$ $W_{landfill} = \sum_i^n (r_{Wland} m_r)_i$ $W_{recy} = \sum_i^n (r_{Wrecy} m_r)_i$		(r <sub>Wland</sub> ) [Kg], the mass of material removed (m <sub>r</sub> ), the fraction of waste to recycling (r <sub>Wrecy</sub> ) [Kg].
HAR habitat report		Reports for affected biodiversity or habitat affected by waste, water, or runoff.
PSI initiatives to mitigate environmental impacts		Initiatives to mitigate environmental impacts of PSS, Energy-saving or value-added services, or recycling strategies implemented.
PSP packaging		Determined through the percentage of packaging materials reclaimed, utilization strategy of lesser, cleaner, or reusable packaging.
EFI fines	Calculated as GHG emission converted from cost (G <sub>cost</sub> )	Environmental impacts by-product while in use or post-use, Cost of environmental impact per unit production, Life cycle cost of the product (C <sub>product</sub> ), GHG emission coefficient of electricity (Ø), and Unit cost of energy (UC <sub>energy</sub> ) [\$].
$G_{cost} = \frac{C_{product}}{UC_{energy}} \times \phi$		
ESA sanctions		The number of monetary sanctions for noncompliance to environmental regulations.
EEX expenditure	Savings or return / investment	Return on investment [\$], investment [\$].
ITR impact	Environmental impact of transporting products	Environmental impact of transporting products, members of the workforce, and other goods and materials.
STR logistics strategy	Transportation or logistics	The introduced strategy of energy-efficient logistics during delivery of products to customers and wastes to post-processing activities.

Literature cited to propose and describe environmental performance indicators are shown in Table 5.2. Among these cited references, 15 mentioned more than 5 SPIs focusing on environmental dimension.

Table 5.2 References cited to propose environmental performance indicators

Literature cited	Environmental performance indicators																										No. of SPI			
	M	M	M	M	M	R	E	E	E	W	W	W	W	L	H	B	G	P	S	S	W	H	P	P	E	E		E	I	S
	A	A	A	A	A	M	N	N	N	A	A	A	A	A	A	D	H	A	A	P	A	A	S	S	F	S		E	T	T
	C	E	A	R	V	A	C	E	R	C	D	I	R	N	B	S	G	P	P	I	S	R	I	P	I	A	X	R	R	
(Ahmad et al., 2018)	×	×	×																											3
(Alarcon et al., 2010)					×																									1
(Badurdeen and Jawahir, 2017)		×		×	×			×	×												×	×						×	×	9
(Behrisch et al., 2011)	×						×	×		×								×			×	×		×	×	×		×	×	12
(Beng and Omar, 2014)					×												×				×	×			×	×				6
(Bereketli and Erol Genevois, 2013)	×			×	×	×	×	×									×	×	×		×	×		×				×	×	13
(Bikas et al., 2016)			×																											1

[illegible]

As shown in Table 5.2, a total of 49 references are included to propose the economic performance indicators at different levels. The symbol ‘×’ represents the mentioning of the SPI in the reference cited. The more number of this symbol, the more the reference focuses on the environmental performance indicators especially on the mentioned SPI.

### 5.3.2 Economic performance indicators

This section reports a measure of the economic performance through economic viability, market presence, and indirect economic impacts. The overall economic performance is related to the minimization of overall cost and improves the value of the product throughout the life cycle. Process-based benefits depend on wider consideration of subcategories. For instance, concerning economic performance cost will not show a proportional increase with an increase in complexity and customization of parts in AM processes than in CM processes, which is one advantage of AM process.

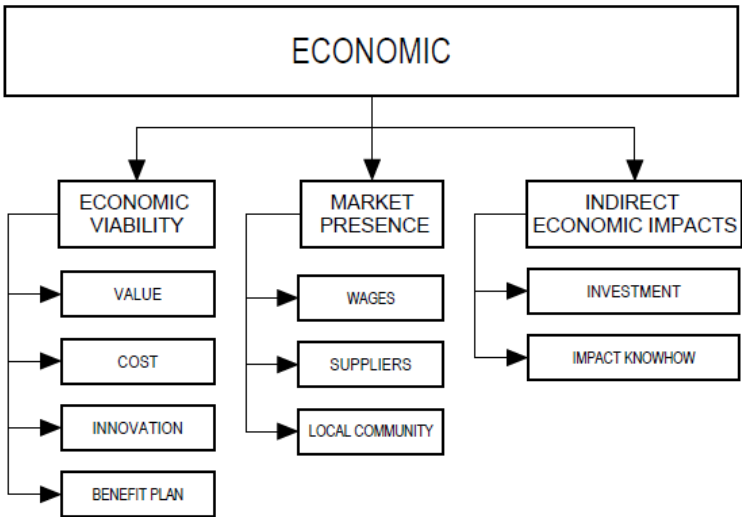


Figure 5.3 Categories and subcategories of economic performance indicators

Figure 5.3 shows categories and subcategories of the economic dimensions of sustainability. It is shown that the three categories are economic viability, market presence, and indirect economic impacts. Moreover, the 9 subcategories for each category are reported. Furthermore, Table 5.3 mentions each SPI for economic dimensions, mechanism of evaluation, and what data is needed to evaluate these SPIs whenever required.

Table 5.3 Economic performance indicators

No.	SPI	Formula (whenever required)	Data needed for SPI evaluation
1.	ECE value	Profit (by using the strategy of minimizing manufacturing and other costs due to a new methodology).	Direct economic value generated by consideration of revenue, operating cost [\$], employee compensation, donations, community investments, payments to the government, etc. Eco-efficiency can be used to measure economic value added by the firm with its aggregated economic impact
2.	ECO cost	By determining the total cost incurred on a product through material utilization, using, and post-use activities.  $C_{Product} = \sum C_{Material} + \sum C_{Use} + \sum C_{EoL}$ By determining costs associated with operation.  $C_{Operating} = \sum_{i=1}^n (m_{cons} C_{cons}_i) + (EC_{onsite}) C_{elec} + t_p C_{lab}$	The total cost of material ( $C_{Material}$ ), the total cost during use ( $C_{Use}$ ), total cost after end of life ( $C_{EoL}$ )  Mass of consumable items ( $m_{cons}$ ), cost of consumables ( $C_{cons}$ ), cost of electrical energy ( $C_{elec}$ ), process time ( $t_p$ ), labor cost ( $C_{lab}$ ).  Material cost on a mass basis ( $P_m$ ), material density ( $\rho$ ), part volume ( $V$ ), the fraction of material scrapped during manufacturing ( $f$ )

Another option, by determining the total cost of a product from costs of material, tooling, equipment, and overhead.

$$C_{\text{Product}} = C_{\text{material}} + C_{\text{tooling}} + C_{\text{equipment}} + C_{\text{overhead}}$$

$$= \left( \frac{P_m \rho V}{1-f} \right) + \frac{C_T N_T}{n} + \frac{1}{r_m} \left[ \frac{C_E}{L t_{wo}} \right] + \frac{r_{oh}}{r_m}$$

Overall cost determined from warranties, maintenance, overhead, depreciation, and insurance.

$$C_O = C_W + C_{MR} + C_{DO} + C_{IO} + C_D + C_I$$

Cost-effectiveness of remanufactured product and a new product. This is mainly measuring the end-of-life costs of a product.

$$\Delta LCC = LCC_n - LCC_{rm}$$

$$LCC_n = LCC_{\text{prod}} + LCC_{\text{EXP}} + LCC_{\text{DP}}$$

$$LCC_{\text{User}} = C_{\text{ProdU}_{rm}} + C_{\text{EXP}} + C_{\text{ILF}} + C_{\text{DP}} - C_{\text{SAL}}$$

$$LCC_{rm} = C_{\text{ProdU}} + C_{\text{SP}} + C_{\text{Cle}} + C_{\text{lab}} + C_{\text{Tra}} + C_{\text{Pac}} + C_{\text{Oth}}$$

Cost of dedicated tooling ( $C_T$ ), number of complete toolsets needed for the production run ( $N_T$ ), number of identical parts desired ( $n$ )

Production rate ( $r_m$ ) – this is the rate at which parts are manufactured, equipment cost ( $C_E$ ) – permanent, time load ( $L$ ) – the fraction of total time at which parts are produced, write-off time ( $t_{wo}$ ) – the life time of the equipment.

Overhead cost rate ( $r_{oh}$ ) – normalized to part production time, tooling cost ( $C_{\text{tooling}}$ ), equipment cost ( $C_{\text{equipment}}$ ), overhead cost ( $C_{\text{overhead}}$ ).

Overall cost ( $C_O$ ), warranties cost ( $C_W$ ), cost of maintenance and repair ( $C_{MR}$ ), direct overhead cost ( $C_{DO}$ ), indirect overhead cost ( $C_{IO}$ ), depreciation cost ( $C_D$ ), insurance cost ( $C_I$ ).

Cost-effectiveness of remanufactured product and a new product ( $\Delta LCC$ ), life cycle cost of new product ( $LCC_n$ ), life cycle cost of the remanufactured product ( $LCC_{rm}$ ).

New product acquisition cost ( $C_{\text{Prod}}$ ), exploitation cost ( $C_{\text{EXP}}$ ), disposal cost ( $C_{\text{DP}}$ )

Life cycle cost from user's perspective ( $LCC_{\text{user}}$ ), used (remanufactured) product acquisition cost from users' perspective ( $C_{\text{ProdU}_{rm}}$ ), the cost associated with insurance, license, and fee ( $C_{\text{ILF}}$ ), salvage value ( $C_{\text{SAL}}$ ).

Used product acquisition cost from remanufacturing perspective ( $C_{\text{ProdU}}$ ), new spare parts cost ( $C_{\text{SP}}$ ), cost of cleaning parts ( $C_{\text{cle}}$ ), transportation

		cost ( $C_{Tra}$ ), packaging cost ( $C_{Pac}$ ), other manufacturing costs ( $C_{Oth}$ ).
3.	IRD innovation	Expenditures associated to innovation, research and development, and/or the total number of implemented innovations.
4.	FBA financial benefit and assistance	Possible financial benefit or assistant received from the government or other sources.
5.	WAG wages	Range of ratios of standard entry-level wage by gender compared with local minimum wage at significant locations of operation.
6.	SUP suppliers	Policy, practices, and proportion of spending on locally-based suppliers at significant locations of operation.
7.	LOC local community	Local hiring or involvement of local community (junior or senior positions) which is introduced due to new product/process/system.
8.	INV investment	Impact of infrastructure investment and services for public benefit through commercial, in-kind, or pro bono engagement.
9.	IMK impact knowhow	Indirect economic impacts such as jobs created by suppliers of the product or raw material.

References cited to propose and describe these economic performance indicators are shown in Table 5.4. Among these cited references, 6 mention over 3 SPIs focusing on economic performance indicators.

Table 5.4 References cited to propose economic performance indicators

Literatures cited	Environmental performance indicators									No. of SPI
	ECE	ECO	IRD	FBA	WAG	SUP	LOC	INV	IMK	
(Badurdeen and Jawahir, 2017)	×	×						×	×	4
(Boks, 2006)					×	×	×			3
(Bonvoisin et al., 2014)		×								1
(Borchardt et al., 2011)					×	×	×			3
(Boulanger, 2008)	×		×	×						3
(Bourell et al., 2017)		×								1
(Bracke et al., 2017)		×								1
(Chong et al., 2018)		×								1
(Cobut et al., 2015)		×								1
(Deutz et al., 2013)		×								1
(Eastwood and Haapala, 2015)	×	×								2
(Emerson et al., 2008)			×	×						2

(Frazier, 2014)	×									1
(Ghobadian et al., 2018)	×									1
(Golinska et al., 2015)	×	×	×							3
(Jayal et al., 2010)	×	×								2
(Jin et al., 2017)	×									1
(Kerbrat et al., 2015)			×	×						2
(Lee et al., 2016)	×									1
(Mathieux et al., 2007)	×									1
(Moktadir et al., 2018)	×	×								2
(Pigosso et al., 2010)	×									1
(Vereinte Nationen, 2007)				×	×	×	×	×		5

As shown in Table 5.4, a total of 23 references are cited to propose the economic performance indicators at different levels. Similarly, the symbol ‘×’ represents the mentioning of the SPI in the reference cited. The more number of this symbol, the more the reference focuses on the economic performance indicators especially on the mentioned SPI.

### 5.3.3 Social performance indicators

The overall social performance is related to the societal impact of processes and products through general health and safety practices, development management, and human rights by an organization. This dimension of sustainability considers aspects of employees, customers, and the surrounding community. Detail description of subcategories of social dimension is reported in Figure 5.4.

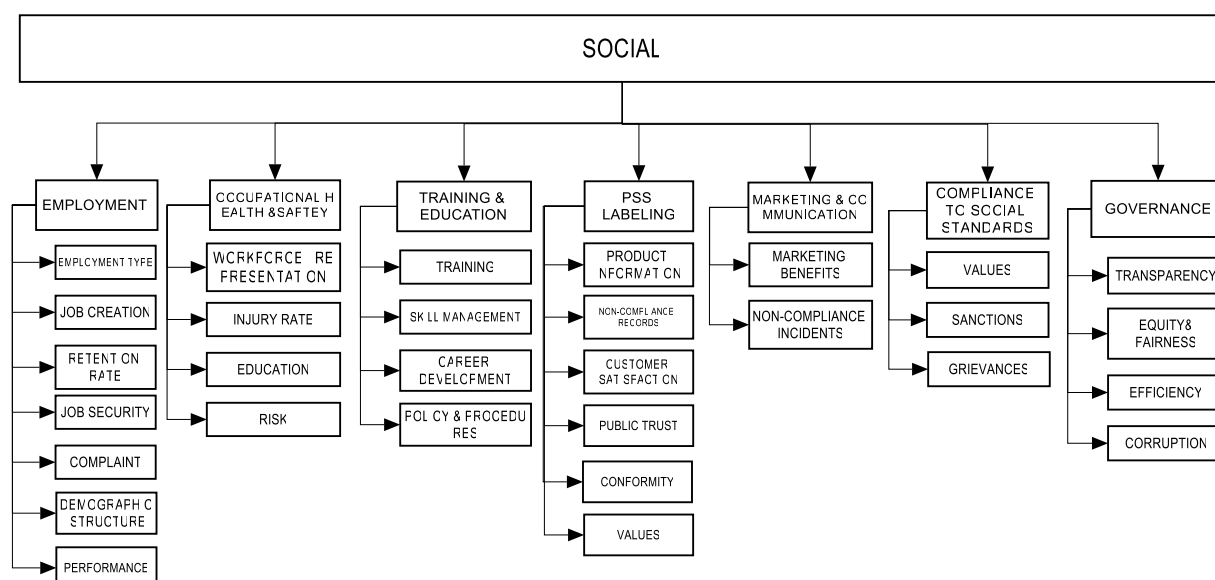


Figure 5.4 Categories and subcategories of social performance indicators

Table 5.5 Social performance indicators

SPI	Formula (whenever required)	Data needed for SPI evaluation
EMT employment type		Total workforce employment type, employment contract, and region by gender. This can also consider the evolution of total employee within time.
EMJ job creation		Rate of new employee hires and employee turnover (by age group, gender, and region). This is related to job creation and accessibility to the labor market
EMR job retention rate		Benefits packages (plans) are provided to full-time or part-time employees to enhance retention.
EMS job security		Incidents of exposure to harmful chemicals, adverse atmospheric conditions, length of working day among others. It also includes workplace safety and comfort.
EMC Compliant		Frequency of complaint reports from employees and associated reasons
EMD demographic structure		Impact of age, gender, and education.
EMP performance		Knowledge, skill, and competence of employees
WFR workforce representation		Percentage of total workforce represented in formal joint management to protect, advise and monitor employees' issue of occupational health and safety (OHS).
INR injury	<p>Injury incident (acute injuries)</p> $INJ = r_{inj} t_p$ <p>Lost working days</p> $LWD = r_{lwd} INJ$ <p>Illness incident</p> $ILL = r_{ill} t_p$	<p>This includes INJ, ILL, LWD, absenteeism, and the total number of work-related fatalities, acute injuries indicate the level of safety within the process work environment. It is calculated as the process injury incident rate multiplied by the processing time.</p> <p>Where</p> <p>Injury incident rate (<math>r_{inj}</math>)</p> <p>Lost working day rate (<math>r_{lwd}</math>) [days]</p> <p>Illness incident rate (<math>r_{ill}</math>) [illness]</p>
EDU education		Education, training, counseling on prevention and risk control programs to assist workforce members, their families, or community members regarding serious diseases and overall OHS
RIS Risk	<p>Human health impact of chemical, c, (<math>I_c</math>)</p> $I_c = f(R_c, T_c)$	This can be expressed in terms of utilization of nonhazardous input material, minimization of the impact of hazardous and/or non-hazardous waste to land and society, and exposure to toxic chemicals,



		mist, and dust that potentially affect human health and ecosystem within the product's life cycle.
		Daily risk of health damage from exposure to chemical, $c$ ( $R_c$ ), the persistence of chemical $c$ in the environment ( $T_c$ ).
TRE training and education		Average hours of training and education per year per employee (user) by gender and by employee category and number of employees within a given time compared to the total number of employees.
SKM skill management		Programs for skill management and lifelong learning supports the continued employability of employees and assist them in managing career endings
CAD career development		Percentage of employees receiving regular performance and career development reviews.
POP policy & procedures		Total hours of employee (user) training on policies and procedures concerning aspects of human rights that are relevant to operations, including the percentage of employees trained
PIN product information		Type of product and service (PSS) information required by procedures, and percentage of significant PSS subject to such information requirements.
		Necessary information including architecture of product, physical and functional relation of each part, life cycle cost, environmental load, emissions of the product and parts.
		Requirements of eco-labeling for environmental performance including energy consumption during use and users' behavior, discomforting effect, the content of hazardous material, service life, disposal strategy, and recycling issues.
NCR noncompliance records		The number of incidents of non-compliance to regulations and voluntary codes concerning PSS information and labeling, by type of outcomes.
CUS customer satisfaction	Determined based on safety, comfort, better value at a reduced cost, etc.	This can be done through the evaluation result of the user-product relationship. Nowadays, end-user satisfaction is becoming a mandatory requirement of all products.
PUT public trust	User-product relationships, the role of culture, user values, and producer responsibility regulation	Producing, protecting, and strengthening the product brand and its reputation to build long-term business liability and success and respond to regulatory constraints and opportunities.

CON Conformity	Designers design a product based on experience but it is necessary to check users' expectations.	Level of quality, comfort, and customization based on needs of customers such as durability, aesthetics, and ergonomic gain
VAL Values		The monetary value of significant fines for non-compliance with laws and regulations concerning the provision and use of PSS.
MAB marketing benefits	New product development must focus on the market, increased number of customers, and frequency of repurchasing or demand.	Programs for adherence to laws, standards, and voluntary codes related to marketing communications (include advertising, promotion, and sponsorship).
NCI noncompliance incidents		Total number of incidents of non-compliance with regulations and voluntary codes concerning marketing benefits
SFI fines		Monetary values of fines for non-compliance with social laws and regulations
SSA sanctions		Non-monetary sanctions for non-compliance with social laws and regulations
SGR grievances		The number of grievances related to human rights filed, addressed, and resolved.
TRP transparency		Composition of the board, independence among members, and compensation of members. Board's executive power, transparency level, and connectivity with stakeholders.
EQF equity & fairness		Equal rights, freedom, and child labor.
EFF Efficiency		Performance of an employee, a team, or a unit in a working day.
COR corruption		Dishonesty will greatly affect the delivery of services, performance, and negatively impact the overall welfare of the organization.

References cited to propose and describe social performance indicators are shown in Table 5.6. Among these references, 7 mention over 5 SPIs focusing on social performance indicators.

Table 5.6 References cited to propose social performance indicators

Literatures cited	Social performance indicators																												No. of SPI		
	E	E	E	E	E	E	E	W	I	E	R	T	S	C	P	P	N	C	P	C	V	M	N	S	S	S	T	E		E	C
	M	M	M	M	M	M	M	F	N	D	I	R	K	A	O	I	C	U	U	O	A	A	C	F	S	G	R	Q		F	O
	T	J	R	S	C	D	P	R	R	U	S	E	M	D	P	N	R	S	T	N	L	B	I	I	A	R	P	F	F	R	
(Badurdeen and Jawahir, 2017)			×							×		×		×					×												5
(Behrisch et al., 2011)																			×												1
(Beng and Omar, 2014)											×																				1
(Bereketli and Erol Genevois, 2013)										×		×									×										3
(Boks, 2006)																		×					×	×							3
(Borchardt et al., 2011)											×										×										2
(Bracke et al., 2017)																	×	×													2

[illegible]

As shown in Table 5.6, a total of 34 references are included to propose the social performance indicators at different levels. Similarly, the symbol ‘×’ represents the mentioning of the SPI in the reference cited. The more number of this symbol, the more the reference focuses on the social performance indicators especially on the mentioned SPI. One can easily observe that some of these references also mentioned indicators on the environmental and economic dimensions which shows a more close sustainability consideration by considering indicators from all dimensions.

Tables 5.2, 5.4, and 5.6 reported the number of references cited and the number of SPI mentioned by each reference as shown in the last column of each table showing how frequently each proposed SPI is mentioned in each cited reference. Thus, it is observed that 48 references are cited for environmental, 23 cited for economic and 34 cited for social performance indicators. Furthermore, the number of indicators proposed from a single reference is much larger in the environmental performance indicators than economic and social performance indicators. For instance, simple observations on these tables show more than 5 SPI are mentioned in 15 references in the environment, 1 reference in the economic dimension, and 7 references in the social dimension. Thus, this is an indication that the environment was the focus of several studies in the past.

## 5.4 Validation

Validation for exhaustiveness of the proposed list of performance indicators is done by comparing to ten of the most widely used indicator sets and guidelines selected by the author since these indicators sets and guidelines tried to address all dimensions of sustainability in different contexts and applications. However, this doesn't mean additional indicator sets and guidelines are not necessary to compare with the proposed list of indicators. Doing this will further strengthen the comprehensiveness of proposed indicators. This method of validation is highly relevant since the indicator sets and guidelines considered a wider range of geography, study field, aspects, and so on. Table 5.7 reports the validation result of each of the 68 SPI concerning selected indicator sets and guidelines.

Table 5.7 Comparison of proposed SPI to selected indicator sets and guidelines

Proposed SPI	Sustainability		Existing indicator sets and guidelines									
	Dimension	Lifecycle stage	GRI 2000	ISO 14031 2013	ESI 2005	EEA 2005	UN ISD 2007	OCED EI 2003	EPRi	DJSI	EPfi	Ford PSI
BDS	EN	All	×	×	×		×	×			×	
CAD	SO	All	×				×					
CON	SO	UP										
COR	SO	PM, MA, UP		×			×	×				
CUS	SO	UP	×	×								×
ECE	EC	PM LO	×	×	×		×			×		×
ECO	EC	PM, UP, LO	×	×	×		×	×	×			×
EDU	SO	PM			×		×					
EEX	EN	PM, UP	×							×	×	
EFF	SO	All					×					
EFI	EN	MA, UP	×	×						×	×	
EMC	SO	All	×									
EMD	SO	All	×				×					
EMJ	SO	All	×							×		
EMP	SO	PM								×		
EMR	SO	PM	×	×								
EMS	SO	PM		×								×
EMT	SO	PM	×							×		
ENC	EN	PM, UP, LO	×	×	×	×	×	×	×		×	
ENE	EN	PM, UP	×	×				×				
ENR	EN	PM	×	×	×	×	×	×	×		×	
EQF	SO	All										
ESA	EN	UP	×								×	
FBA	EC	All	×									
GHG	EN	MA, UP, LO	×	×	×	×	×	×			×	
HAB	EN	SO	×			×						
HAR	EN	All	×	×	×	×	×		×			
IMK	EC	MA, UP, LO	×				×					
INR	SO	PM	×									
INV	EC	PM	×									
IRD	EC	PM		×								
ITR	EN	LO	×					×			×	
LAN	EN	SO	×	×		×			×			
LOC	EC	All	×									
MAA	EN	PM	×	×				×	×			×

## Sustainability Performance Indicators

MAB	SO	UP	×									
MAC	EN	PM	×	×		×	×	×				
MAE	EN	PM		×	×	×	×	×	×			
MAR	EN	PM	×	×					×			
MAV	EN	UP		×								×
NCI	SO	UP	×									
NCR	SO	UP	×									
PAP	EN	PM, UP	×	×	×	×	×	×	×	×	×	×
PIN	SO	UP	×	×	×	×	×	×				×
POP	SO	All	×									
PSI	EN	UP	×	×				×		×	×	
PSP	EN	UP	×	×				×				×
PUT	SO	UP										
RIS	SO	PM	×		×		×	×			×	×
RMA	EN	PM	×	×				×	×			
SAP	EN	PM	×	×	×	×	×	×	×	×		
SFI	SO	PM	×									
SGR	SO	All	×									
SKM	SO	PM	×				×					
SPI	EN	PM	×	×	×	×	×		×		×	
SSA	SO	All										
STR	EN	LO	×	×		×		×			×	
SUP	EC	UP	×									
TRE	SO	PM, LO	×				×			×		
TRP	SO	All										
VAL	SO	All	×									
WAC	EN	PM	×	×	×	×	×	×	×		×	
WAD	EN	PM		×	×	×	×					
WAG	EC	PM	×				×					
WAI	EN	PM, SO	×	×	×	×	×	×			×	
WAR	EN	PM	×	×		×	×	×	×			
WAS	EN	PM LO	×	×	×		×		×			
WFR	SO	All	×	×			×			×		×

### Key:

GRI 2000	Sustainability Reporting Guidelines
ISO 14031 2013	Environmental management - Environmental performance evaluation - Guidelines
ESI 2005	Environmental Sustainability Index: Benchmarking National Environmental Stewardship
EEA 2005	European Environment Agency core set of indicators - Guide
UN-SD2007	Indicators for Sustainable Development: Guidelines and Methodologies
OCED EI 2003	Environmental Indicators: development, measurement, and use
EPrI	Environmental Pressure Indicators for the EU
DJSI	Dow Jones Sustainability Index and Total Quality Management
EPfi	2010 Environmental Performance Index
Ford PSI	Product Sustainability Index by Ford of Europe

Results of validation for exhaustiveness based on the ten indicator sets and guidelines are reported in Table 5.7. It is found out that 43 indicators among the total 68 proposed SPIs, are mentioned in 2 to 9 of these sets of indicators and guidelines with the symbol '×'. But the remaining 15 indicators are mentioned only once and 5 are never mentioned in each of these

indicator sets and guidelines. All the 5 indicators that are never mentioned are all social PIs and among those mentioned only once, 11 are social and only 4 are economic PIs. The 5 social PIs are conformity, equity and fairness, public trust, social sanctions, and transparency and the 4 economic PIs mentioned only one is focusing on investment, innovation employment of local community, and location of operation for suppliers' benefit. Moreover, as described in the background of this study, this result proves that the most widely known indicators sets and guidelines focused on environmental and economic aspects and little or no consideration for social aspects of sustainability. Thus, this reaffirms the contribution of this study on a broader consideration of SPIs by at least 20 more indicators and strengthening balanced consideration of all the three dimensions of sustainability.

The ten representative indicator sets and guidelines are studied to perform validation for exhaustiveness for the proposed SPIs but additional guidelines or indicator sets could be further supplemented as far as associated with sustainability performance. However, in section 5.2, it is explained that there are subjective understandings in the term sustainability itself, which is reflected on each of the ten indicator sets and guidelines mentioned in this study. One can easily understand that though sustainability is the key focus, the goals or objectives of each indicator set and guideline are dominated by environmental dimensions than other dimensions. The following paragraphs explain considerations and points of view of each indicator set or guideline.

*GRI 2000* is a guideline developed based on the goal and key challenges of understanding sustainable development. It considered the need for urgency and magnitude of risks and threats towards assuring sustainability and to increase opportunities of making transparency about economic, environmental, and social impacts. It is established based on supporting expectations, communicating sustainability well, and relies on the collaboration of a large network of experts from different stakeholder groups, investment decisions, and other market relations.

*ISO 14031 2013* gives guidance on the design and use of environmental performance evaluation (EPE) within an organization, regardless of type, size, location, and complexity. It is developed by the committee, ISO/TC 207, environmental management, subcommittee SC4, environmental performance evaluation. Furthermore, it took the effort of many organizations' interest to understand, demonstrate and improve their environmental performance. Managing their activities, products, and services can significantly impact the environment.

*ESI 2005* is a sustainability index published by Yale Center for Environmental Law and Policy based on experts' workshop in 2004. It is developed based on the assessment of available data, rigorous analysis and consultation with policymakers, scientists, and indicator experts, and also the association of environmental sustainability and challenges to development and industrialization as well as factors of underdevelopment and poverty-induced environmental challenges. It integrates 76 data sets, tracking natural resources, past and present pollution

levels, environmental management efforts, and capacity of a society to improve its environmental performance into 21 indicators of environmental sustainability. It focuses on issues related to environmental systems, reducing environmental stresses, reducing human vulnerability, societal and institutional capacity, and global stewardship. Furthermore, it considers the relationship between environmental sustainability and economic development.

*EEA 2005* produced an indicator core set selected based on criteria widely used in Europe and the OECD. Particular attention to policy priorities, objectives, and targets. It focuses on improving coverage of data flows manageable and stable basis for indicator-based assessments of progress against environmental policy priorities. This core set covers six environmental themes; air pollution and ozone depletion, climate change, waste, water, biodiversity, and terrestrial environment and four sectors: agriculture, energy, transport, and fisheries.

*UN-ISD2007* holds sets of indicators of sustainable development based on the functions of indicators to make better decisions and more effective actions by simplifying, clarifying, and making aggregated information available for policymakers. It is developed through a wide range of participation from governments, international organizations, academic institutions, non-governmental organizations, and individual experts.

*OCED EI 2003* is proposed based on the relevance of indicators for environmental reporting, measurement of environmental performance, and reporting on progress towards sustainable development. It is designed to create a common approach and harmonization of individual interests of OECD member countries, further development and use of environmental indicators, promote an exchange of related experience to non-members. It is intended to support policy analysis and evaluation by OECD and measure environmental progress and performance, monitor policy integration and allow effective international comparisons.

*EPrI* considers the background of utilizing indicators widely used in economic and social policymaking and understanding pressures on the environment from human activities. It helps better understanding the relevance of having sound knowledge of the current environmental problems and creates a basis for future environmental policies. It is developed based on considering policy fields on resource depletion, waste, dispersion of toxic substances, water pollution, marine environment, and coastal zones, climate change, air pollution, ozone depletion, and urban environmental problems.

*DJSI* is created to track and monitor organizations' performance as they strive to increase long-term stakeholder value during the transition from total quality management (TQM) to sustainable management. It is known that the theory and practice of TQM have evolved over decades from technical aspects of quality control and employee training to supply-chain-wide delivery of excellent products and services and now organizations managed to make the transition

to sustainable management where efforts are captured, measured, and reported as economic, environmental and social (TBL) benefits.

*EPfI* considers environmental sustainability as a critical policy focus and public agenda across the world. Further attention is given to climate change, water quality and availability, air pollution, deforestation, and land-use changes, biodiversity, and sustainability of agriculture and fisheries. This environmental performance index ranks 163 countries on 25 performance indicators covering both environmental public health and economic system vitality. It helps in environmental decision making, the potential for better metrics and more refined policy analysis, better data collection, methodologically consistent reporting, mechanisms for verification and commitment to environmental data transparency, clear policy target, and environmental challenges.

*Ford PSI* reports the sustainability management tool introduced by Ford. It is introduced based on consideration of environmental, economic, and societal aspects into product development of the new Ford Galaxy and Ford S-MAX. It takes considerations on environmental and cost aspects based on life cycle assessment and life cycle cost, sustainable materials, safety, mobility capacity, and noise.

## **5.5 Conclusion**

This study proposed a new, comprehensive list and interpretation of sustainable performance indicators by assessing and understanding current achievements and observed gaps in sustainability, sustainability dimensions, and associated indicators as well as opportunities in current trends in design and manufacturing. Identifying gaps and assessing future opportunities of the manufacturing system based on globalization and increasing demands on sustainable performance and social responsibility concerns is considered as highly significant input.

Outcomes on background assessment further attested that there exist subjective understandings on sustainability itself depending on goal or scope of assessed specific studies, unbalanced and incomplete consideration of performance indicators, giving more concern for environmental dimensions than the other two dimensions, lack of standardization, detailed description and measuring strategies. Moreover, it is understood that focus on the design stage which is mentioned to decide 80% of sustainability impacts and product's life cycle consideration are additional gaps in considering sustainability performance evaluation which is taken as a stimulus for this study.

Requirements during all stages of the product life cycle (pre-manufacturing, manufacturing, use, post-use, and logistics) aspects are taken into account. The study in Chapter 4, about analyzing the sustainable performance of additive manufacturing from a product life cycle perspective, is



found out that there is a better trend of addressing all dimensions of sustainability based on initial investigation of key opportunities of additive over conventional manufacturing processes. This is possible through proper design adaptation and appropriate parameter selections which can be associated with the growing trend of the shift towards additive manufacturing.

This study proposed 18 second-level categories of indicators, 8 for the environment, 3 for economic and 7 for social, and 68 third level subcategory where 29 are for the environment, 9 for economic, and 30 for social dimensions. For each subcategory detailed interpretation and whenever necessary a formulation on how to evaluate each indicator of the subcategory as well as the requirement of necessary data to determine each indicator is reported. Finally, validation for exhaustiveness of the proposed list of sustainable performance indicators by considering ten of the most widely used indicator sets and guidelines.

It is identified that among the 68 indicators, 43 of these indicators are mentioned in 2 to 9 of these indicator sets whereas 15 indicators are mentioned once and 5 indicators are never mentioned. Those indicators are never mentioned and the majority of indicators mentioned only once are social performance indicators, which is taken as an indication for lack of equal consideration of this dimension of sustainability as compared to economic and environmental dimensions. To sum up, as key contributions of this study a comprehensive list of sustainability performance indicators is proposed and interpreted as well as validated for its exhaustiveness by considering more social performance indicators for balanced and exhaustive consideration of all dimensions for sustainability evaluation.

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## Chapter 6

### Sustainability Evaluation of Manufacturing Processes

#### 6.1 Introduction

The development of a comprehensive list of sustainability performance indicators (SPI) in Chapter 5 for the three dimensions will be an important input in sustainability evaluation using multicriteria decision-making methodology since it consists of conflicting criteria. A total of 68 SPIs from all three dimensions are reported where decision-makers tend to select relevant SPI to contribute to better sustainability performance. However, for the sake of the simplified evaluation, those indicators with relevance to selected manufacturing processes and sustainability are chosen based on the literature and experience of authors for the selected application. Decision-makers tend to select SPIs that have better importance/impact. For this specific case, some indicators that are indirectly expressed in terms of another indicator within the same category are not taken into consideration.

A case of Faceshield bracket manufacturing is taken as an application. This analysis helps decision makers how MCDM using AHP methodology is used to choose processes for better sustainability performance. A method of multicriteria decision-making methodology of AHP is utilized. The analysis is done for three manufacturing processes as the three alternatives. These are injection molding, 3D printing, and laser cutting. Finally, the sustainability performance of each process is reported for each dimension by considering the selected SPI from the list proposed in Chapter 5.

#### 6.2 Decision-making methodologies for product development

Within the scope of this study, the analytic hierarchy process is utilized for multicriteria decision making and Borda count methodology to assist decision-makers in making the final preference based on broadly acceptable preferences rather than the majority. Further explanation of each method is reported below.

##### 6.2.1 Analytic Hierarchy Process methodology

Analytic Hierarchy Process (AHP) is selected for the fact that it is widely accepted and applied, can evaluate qualitative and quantitative criteria on the same preference scale, easier hierarchical modeling or problem structuring, adopt verbal judgments, and allows verification of consistency. The method uses pairwise comparisons to simplify preference ratings among decision criteria and provides measures of judgment consistency and drives priorities among criteria and alternatives. Inputs can either actual measurements or subjective judgments from decision-makers.



Consistency verification is possible in AHP via ratio scales (RI) derived from principal eigenvectors and consistency index (CI) derived from the principal eigenvalue. Among the alternatives, the method helps to determine the most relevant alternative, depending on the priority given to each of the criteria taken into account consideration. The stages utilized for better implementation of this method are shown in the flowchart shown in Figure 6.1.

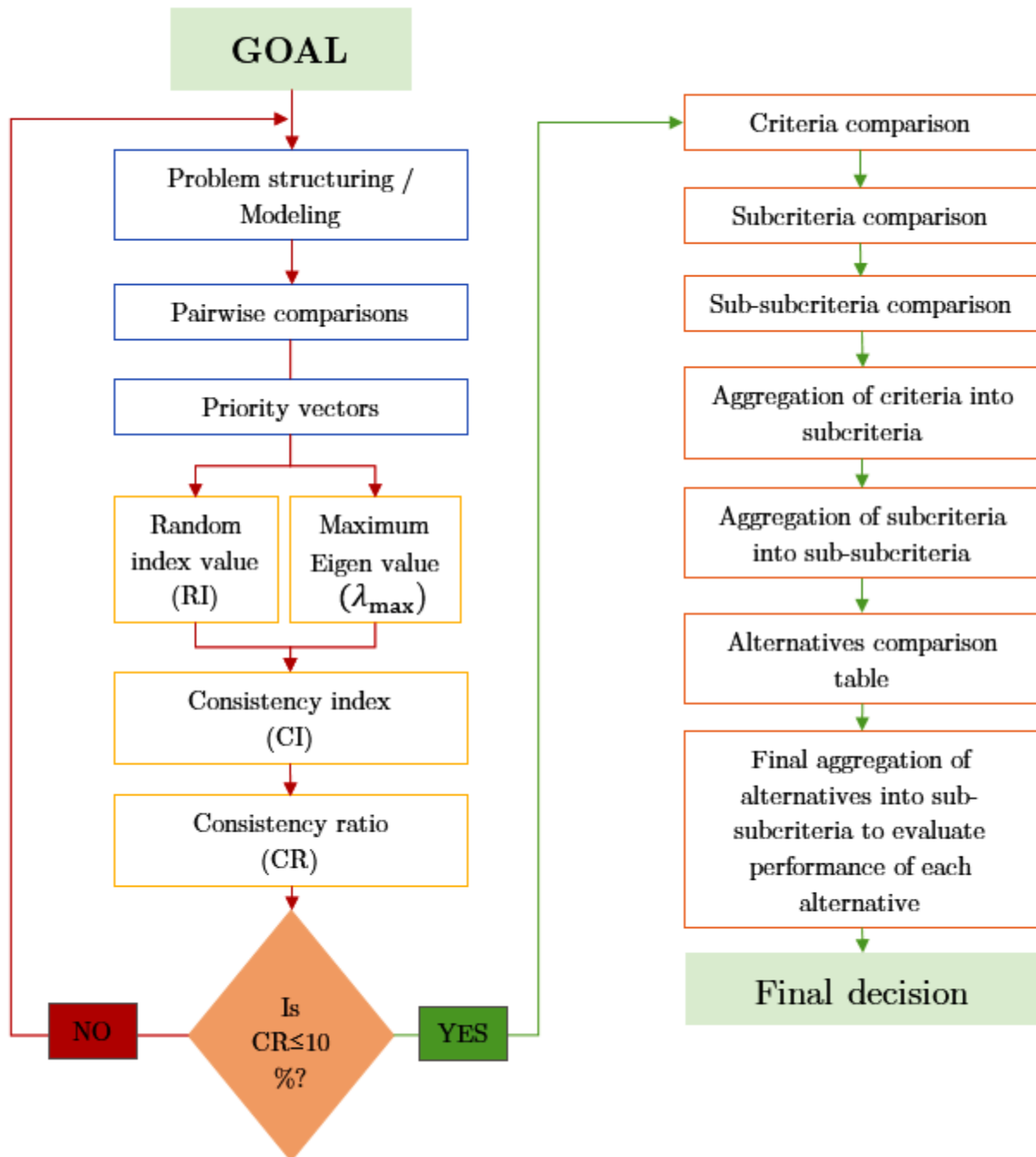


Figure 6.1 Flowchart of the AHP decision-making process

### Problem structuring/modeling

Figure 6.1 represents a flowchart of the AHP decision-making process and a description of each step is reported below. The first stage shown in the flowchart is structuring or modeling the problem where this stage requires establishing indicators' tree after identifying indicators or most important and influential SPIs from the whole list. Once the important SPIs are selected, judgments are given to set up the pairwise comparison matrix as mentioned in Equation 6.1.

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{21} & \dots & a_{ij} & \dots \\ \dots & \dots & \dots & \dots \\ 1/a_{n1} & \dots & \dots & 1 \end{bmatrix} \quad \text{Equation 6.1}$$

### Pairwise comparisons

In this step of constructing pairwise comparisons, the relative importance of the factors will be checked for factors at the higher level. The number and size of the matrix depend on the SPI included for each level. Pairwise comparison considers comparing the relative importance of two items (within criteria, subcriteria, or sub-subcriteria) based on selection and judgments made based on the experience of the decision-makers which is based on Saaty's rule. The synthesis of the pairwise matrices is done by determining weights and priorities.

### Weights and priorities

Here, it is necessary to find the priority vector for each matrix, which is the principal eigenvector of the matrix. The priorities of elements in the lower level of the hierarchy are calculated first and then it progresses back to the upper level to get the overall priority vector. To calculate the vectors of priorities, the Average normalized column method (ANC) method can be used besides the eigenvalue method as described mathematically below.

$$w_{ij} = \frac{a_{ij}}{\sum_{i=1, j=1}^n a_{ij}}, \forall_{i, \text{row } j, \text{column}} \quad \text{Equation 6.2}$$

$a_{ij}$  Numerical equivalent of the comparison between i and j

$n$  Number of criteria or subcriteria or sub-subcriteria

The normalized pairwise comparison matrix is represented in Equation 6.3

$$A_{norm} = \begin{bmatrix} 1 & w_{12} & \dots & w_{1n} \\ w_{21} & \dots & w_{ij} & \dots \\ \dots & \dots & \dots & \dots \\ w_{n1} & \dots & \dots & 1 \end{bmatrix} \quad \text{Equation 6.3}$$

Based on the information arranged in the indicators' tree further synthesis is done to determine relative rankings of alternatives. Detailed criteria (qualitative and quantitative) are compared using informed judgments ('I think') to drive weights and priorities. By using pairwise comparisons, it is easy to express the relative importance of one criterion over another. The matrix is then changed into the ranking of criteria. Determining the eigenvector permits to get priorities from a pairwise matrix.

According to (Alonso and Lamata, 2005), the matrix of a pair comparisons is expressed as  $A = [a_{ij}]$  which represents the intensities of the experts' preference between individual pairs of alternatives ( $A_i$  versus  $A_j$ , for all  $i, j = 1, 2, \dots, n$ ) chosen from a given scale (9, 8, ..., 1/8, 1/9). Given all  $n$  alternatives, a decision-maker compares a pair of alternatives for all possible pairs  $n(n-1)/2$ , and a comparison matrix  $A$  is obtained, where the element  $a_{ij}$  shows a preference weight  $A_i$  obtained by comparing with  $A_j$ . The  $a_{ij}$  elements estimate the ratios  $w_i/w_j$  where  $W$  is the vector of current weights of the alternative, which is our goal. All the ratios are positive and satisfy the reciprocity property  $a_{ij} = 1/a_{ji} \forall i, j = 1, 2, \dots, n$

### Consistency Verification

Measuring consistency helps in accepting or rejecting matrices in the AHP since subjective judgments are made in the definition of the matrices which may result in possible inconsistency. Thus, it is necessary to check for consistency as it is one of the most important advantages of AHP. For the size of a defined matrix ( $n$ ) and the maximum eigenvalue of the pairwise comparison matrix ( $\lambda_{max}$ ), the closer the value of  $\lambda_{max}$  to  $n$ , the more consistent the judgment is. Concerning consistency ratio (CR), if  $CR < 1$ , the judgment matrix is acceptable or consistent, and if  $CR > 0.1$ , it is inconsistent and the matrix should be reviewed.

The eigenvector is the usual method for computing the ranking and weight of alternatives in the AHP. The weight of the vector is the eigenvector corresponding to the maximum value  $\lambda_{max}$  of matrix  $A$ , which is positive and real according to Perron-Frobenius theorem. This is the largest eigenvalue of the matrix. The vector  $w$  can be chosen with all positive coordinates. It is a normalized solution of the equation  $Aw = \lambda_{max} w$ . The traditional eigenvector method for estimating weights in the AHP yields a way of measuring the consistency of the decision maker's

preferences arranged in the comparison matrix. The criteria weight vector is the average value of each entry of the normalized vector as represented in equation 6.4 and the maximum eigenvalue is represented in equation 6.5.

$$W_i = \begin{bmatrix} W_i \\ \dots \\ \dots \\ W_n \end{bmatrix} \quad \text{Equation 6.4}$$

$$\text{Where } W_i, \forall_{i=1 \text{ to } n} = \frac{\sum_{i=1}^n w_{i1}}{n}$$

$$\lambda_{\max} = \sum_{i,j=1}^n \left( \frac{W_i}{w_{ij}} \right) \quad \text{Equation 6.5}$$

The consistency index (CI) is given by Equation 6.6. According to (Saaty and Vargas, 2012), if the referee is completely consistent, " $a_{ij} \cdot a_{jk} = a_{ik} (\forall_{ijk})$ ", " $\lambda_{\max} = n$ " and " $CI = 0$ " and if the referee is not consistent " $\lambda_{\max} > n$ " which encouraged Saaty to propose the following index of measuring consistency with the help of Equation 6.7 where RI is the average value of CI for random matrices using the Saaty scale and CR is a normalized value, because it is divided by arithmetic mean of random matrices consistency indexes. In the ideal case of consistency " $\lambda_{\max} = n$ ", the relations between the weights  $w_i$  and the judgments  $a_{ij}$  will be given by  $w_i/w_j = a_{ij}$  for all  $j, j = 1, 2, \dots, n$

If  $a_{ij}$  represents the importance of alternative  $i$  over alternative  $j$  and  $a_{jk}$  represents the importance of alternative  $j$  over  $k$ , then  $a_{ik} = a_{ij} \times a_{jk} = a_{ik}$  (which represents the importance of alternative  $i$  over an alternative  $k$ ). This condition must be satisfied so that judgments are consistent.

Then, the problem will become  $A'w' = \lambda_{\max} w'$  where  $\lambda_{\max}$  the principal (largest) eigenvalue of is  $A' = (a'_{ij})$ . The (') representing the transpose of a matrix or reciprocal of each value.

Note that for the given matrix of pairwise comparison (A),  $a'_{ji} = 1/a_{ij}$  and,  $A'w' = \lambda_{\max} w'$  can be written as  $Aw = \lambda_{\max} w$ , for the sake of simplicity.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad \text{Equation 6.6}$$

$$CR = \frac{CI}{RI} \quad \text{Equation 6.7}$$

Saaty suggests that a consistency index less or equal to 0.10 indicates that the decision-maker has adequately structured the problem in question, but if the consistency index is greater than 0.10 then the response by subject can be considered as random.

Evaluating the sustainable performance of these processes is equivalent to evaluating the performance of the processes concerning all of these criteria. A methodological problem then arises to define the decision-making strategy that leads to an evaluation and a choice. To enable the decision-maker to make the right choice, several methods have been developed in the multi-criteria context since the 1960s. These methods then help direct the decision-maker towards a judicious compromise rather than an often outdated optimum (BenMena, 2000).

A very large number of multi-criteria methods can be identified, which can be seen as a strength or a weakness (Bouyssou et al., 1993). This multiplicity of aggregation methods can be explained by the fact that no method completely meets the requirements expected by the user (Schärlig, 1985). Thus, depending on how performance is aggregated, analysts will have to adapt their approaches. However, most of these methods belong to one of the following three operational approaches (Roy and Giard, 1985):

- The single criterion synthesis approach;
- The Synthesis Outranking Approach;
- The interactive local judgment approach with trial-and-error iterations.

Within the framework of this research work, we have chosen to place ourselves within the framework of the single criterion of synthesis approach to evacuate any incomparability. Preferences have then introduced a priority. They are aggregated into a single (value, utility) function which is then optimized. The main methods belonging to this approach are Weighted sum, MAUT (Fishburn, 1970; Vincke, 1989), SMART (Edwards, 1971), UTA (Jacquet-Lagreze and Siskos, 1982), TOPSIS (Hwang and Yoon, 1981), AHP (Saaty, 1980) and G.P (Ignizio, 1978).

For decision makers' judgment, the fundamental comparison scale shown in Table 6.1 is utilized and these scales of values are validated for effectiveness both in applications and theoretical justifications, to represent the intensity of judgments. These scales are used to determine how many times one criteria, subcriteria or alternative is larger than the other.

Table 6.1 Fundamental comparison scale (Saaty and Vargas, 2012)

Intensity of importance	Definition	Explanation
1;2	Equal importance; weak	Two activities contribute equally to the objective.
3;4	Moderate importance; moderate plus	Experience and judgment slightly favor one activity over another.
5;6	Strong importance; strong plus	Experience and judgment strongly favor one activity over another.
7;8	Very strong; very, very strong	An activity is favored very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence of favoring one activity over another is of the highest possible order of affirmation.

As represented in Figure 6.1, AHP decision-making process passes through major steps of determining pairwise matrix analysis, comparison matrix judgment, determination of priority vectors and maximum eigenvalue, consistency verification and finally calculating the complete criteria comparison. The mathematical formulation is generally presented and adjusted whenever the level changes. A square matrix ( $A$ ) of size  $n$  for each level and corresponding normalized matrix,  $A_{norm}$  and criteria weight vector  $w_{ij}$ . The elements of the matrix are represented by  $a_{ij}$ , corresponding to  $i^{th}$  row and  $j^{th}$  column. Similarly, for consistency verification, the average consistency index proposed by (Saaty and Vargas, 2012) is utilized as reported in Table 6.2.

Table 6.2 Average random consistency index (Saaty and Vargas, 2012)

N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

### 6.2.2 Borda count method

Borda count, named after the French mathematician Jean Charles de Borda, is a preferential voting system where the voter declares a ranks candidates in order of preference. The Borda count method determines the winner of an election by giving each candidate, the total number of points corresponding to the number of candidates ranked lower. It considers voting preference to identify at least the best possible compromise and at most the collective wisdom where the voting system shouldn't be an adversarial proceeding in which a majority wins everything while the minority wins nothing (Emerson, 2013). This means this method tends to prefer broadly acceptable candidates, rather than those supported by the majority.

In the Borda count method applied in this study, preferences are awarded points as first, second, last as  $(n, n-1, \dots, 1)$  or more frequently,  $(n-1, n-2, \dots, 0)$ . In the event of one or more persons submitting a partial vote, however, outcomes may vary considerably. Information needed to

apply Borda count in the rankings as first, second, ..., last, and the frequency of preference or how many times each preference is mentioned.

### **6.3 Data collection**

When products are manufactured for the market, product brands and specification details are based on the most important factors for product design and manufacturing including human (occupational) safety, weight, cost, the effect on the environment (post-use), wear resistance, ease of manufacturing, comfort, compatibility and other additional design features such as adjustable straps, fasteners, etc. This has been used as an initial strategy for indicator selection through understanding design and innovation trends in Faceshield bracket and components manufacturing for various similar applications. Recent studies focus on materials used for medical equipment to keep their place in the market based on different considerations. Concerning material used, major criteria include price, versatility with type, availability measured depending on its abundance, mechanical behavior, ease of shaping to complex forms and features, density, and compatibility with the human body which may not cause an allergic effect (Gallo et al., 2019; Garrigou et al., 2020; Rewar et al., 2016; Rim et al., 2013; Sapoval et al., 2020).

Sustainability measure considers as much information as possible regarding the sets of performance indicators, which will be used to measure overall sustainability performance. These indicators can be categorized into three major dimensions as environment, economic and social performances. Major criteria include comfort, cost, quality, durability, flexibility, style, time to market, waste, etc. Moreover, marketing authorization makes sure that the product's safe for human health and the environment during use and it doesn't create health, safety, and occupational risks during manufacturing or post-use. Data gathering is done by collecting quantitative measurements taken from designers and manufacturers of brackets by supplementing experts' opinions and literature surveys.

Finally, the structuring of indicator sets is arranged based on 38 of the most preferred indicators (sub-subcriteria) among the 68 sustainability performance indicators proposed by (Taddese et al., 2020), presented in Chapter 5. Data collection for experts' judgment as well as indicator selection for this study is done based on the 68 indicators is done as reported in Appendix A. This table reported as data collection for utilized for this study but helped to evaluate value or description of each alternative and a description section to assist data collection. Some values are represented the same for each alternative and some values may be difficult to predict and in this case, decision-makers tend to exclude the list and declare that the final decision is done without considering part of the sustainability performance indicators with proper justification.

#### 6.4 A case: Sustainability evaluation of Faceshield bracket manufacturing

The whole world, especially healthcare workers faced a shortage of sufficient PPE and healthcare facilities during the unprecedented outbreak of coronavirus (Covid-19) which was a big challenge for all countries in the world. During this period, several 3D printing industrialists including Ford Motor company worked to manufacture 3D printed Personal Protective Equipment (PPE) (Flanagan and Ballard, 2020). As part of a solidarity effort to the CHU de Clermont-Ferrand, a University hospital center in Clermont-Ferrand, France, in its effort of preventing transmission of Covid-19 outbreak, the Sigma Clermont successfully manufactured three different Faceshield brackets by using injection molding, 3D printing, and laser cutting as shown in Figure 6.2. Enhancing such efforts helped to make an immediate delivery at least to local hospitals to tackle shortages of PPE. Such dispersed efforts of producing PPE in different workshops require proper knowledge of design procedure, the inclusion of mandatory features and preconditions for the intended purpose not to compromise expected quality, the effectiveness of protection (well fit for purpose), and necessity in considerations on sustainability aspects of manufacturing and using such products.

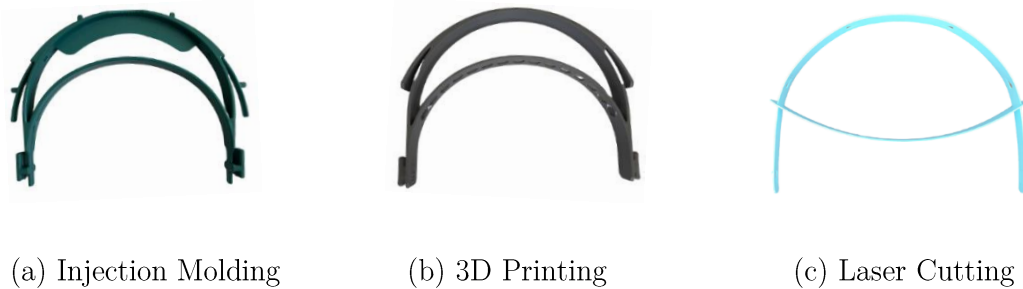


Figure 6.2 Faceshield brackets, Manufactured by Sigma Clermont

This study proposes a method for sustainability evaluation of manufacturing methods, including Additive Manufacturing. The question is to evaluate performance in the sustainability of additive manufacturing. This method is applied to the process used to manufacture Faceshield brackets at Sigma Clermont. The current and future relevance of this study is to develop a sustainability evaluation approach for such various components of Faceshield as a documentation initiative for sustainability performance of the manufacturing methods utilized. Moreover, we are in the era of considering manufacturing beyond the fabrication of a product where it is becoming an integrated concept of all production phases and there is an increased demand for products such as PPE which may lead to a trend in the manufacturing of Faceshield which is costly and unsafe.

##### 6.4.1 Indicator selection strategy

Among the 68 indicators, the selection of the 38 indicators for this study is done based on relevance and immediate impact for the sustainable performance of each of the three



manufacturing processes for the selected case within this scope of this study. After identifying relevant sustainability performance indicators (SPIs), weighting and priority vector derivation is performed by using the AHP method.

Table 6.3 represents a category of selected subcriteria and sub-subcriteria for each of the three sustainability criteria and further explanation of each of this selected sub-subcriteria is reported in section 6.4.3. Environmental indicators are listed within subcriteria of material, energy, emission, conformance, and transport criteria. Economic indicators are listed within subcriteria of viability, marketing presence, and indirect impact criteria. Social indicators are listed within subcriteria of employment, health, training, product service, and labeling and governance.

Table 6.3 Category of included SPIs for the selected case

Sustainability criteria	Subcriteria	Sub-subcriteria	Abbreviation
Environment (C <sub>1</sub> )	Material (SC <sub>1</sub> )	Consumption (SSC <sub>1</sub> )	MAC
		Efficiency (SSC <sub>2</sub> )	MAE
		Availability (SSC <sub>3</sub> )	MAA
		Value recovery (SSC <sub>4</sub> )	MAV
	Energy (SC <sub>2</sub> )	Consumption (SSC <sub>5</sub> )	ENC
		Renewables (SSC <sub>6</sub> )	ENR
	Emission, effluent, and waste (SC <sub>3</sub> )	GHG emission (SSC <sub>7</sub> )	GHG
		Primary air pollutants (SSC <sub>8</sub> )	PAP
		Secondary air pollutants (SSC <sub>9</sub> )	SAP
		Waste (SSC <sub>10</sub> )	WAS
	Conformance (SC <sub>4</sub> )	Monetary values of fines (SSC <sub>11</sub> )	EFI
		Nonmonetary sanctions (SSC <sub>12</sub> )	ESA
		Expenditure (SSC <sub>13</sub> )	EEX
	Transport (SC <sub>5</sub> )	Impact (SSC <sub>14</sub> )	ITR
		Strategy (SSC <sub>15</sub> )	STR
Economic (C <sub>2</sub> )	Economic viability (SC <sub>6</sub> )	Value (SSC <sub>16</sub> )	ECE
		Cost (SSC <sub>17</sub> )	ECO
		Innovation (SSC <sub>18</sub> )	IRD
		Benefit plan (SSC <sub>19</sub> )	FBA
		Wages (SSC <sub>20</sub> )	WAG
	Marketing presence (SC <sub>7</sub> )	Suppliers (SSC <sub>21</sub> )	SUP
		Local community (SSC <sub>22</sub> )	LOC
		Investment (SSC <sub>23</sub> )	INV
	Indirect economic impact (SC <sub>8</sub> )	Impact knowhow (SSC <sub>24</sub> )	IMK
		Employment type (SSC <sub>25</sub> )	EMT
Social (C <sub>3</sub> )	Employment (SC <sub>9</sub> )	Job creation (SSC <sub>26</sub> )	EMJ
		Job security (SSC <sub>27</sub> )	EMS
		Performance (SSC <sub>28</sub> )	EMP
		Injury rate (SSC <sub>29</sub> )	INJ
	Occupational health & safety (SC <sub>10</sub> )	Risk (SSC <sub>30</sub> )	RIS
		Training (SSC <sub>30</sub> )	TRE
	Training and education (SC <sub>11</sub> )	Skill management (SSC <sub>31</sub> )	SKM
		Career development (SSC <sub>33</sub> )	CAD
		Customer satisfaction (SSC <sub>34</sub> )	CUS
	Product and service labeling (SC <sub>12</sub> )		

Governance (SC <sub>13</sub> )	Conformity (SSC <sub>35</sub> )	CON
	Values (SSC <sub>36</sub> )	VAL
	Equity and fairness (SSC <sub>37</sub> )	EQF
	Efficiency (SSC <sub>38</sub> )	EFF

Furthermore, the category of the excluded list of SPI is reported in Table 6.4. This exclusion is done based on the fact that either the indicator doesn't have direct relevance for sustainable performance evaluation of this specific case or their impact is similar. Data collected for indicator selection [Appendix A] is utilized as supportive information to make inclusion and exclusion of SPIs based on the fact that contribution is either equal or no direct data could be fetched for alternative processes. The list of SPI reported in Appendix A for data collection doesn't include all sub-subcriteria (14 SPI) within the subcriteria from the environment dimension (water, biodiversity, and product & service) and from the social dimension (marketing & communication and compliance to social standards) which are entirely excluded before data collection. Exclusion of an additional 16 SPI is done based on the fact that their immediate impact on sustainability evaluation for the selected product and alternatives are either equal or not relevant (EQ/RL) due to lack of data. The final list of excluded SPI, 30 in total, is reported in Table 6.3. However, if a different case considers different products and/or processes, more of these indicators may be included depending on their contribution as far as decision-makers can make judgments for the alternative processes.

Table 6.4 Category excluded SPIs for the selected case

Sustainability criteria	Subcriteria	Sub-subcriteria	Abb.	Reason
<b>Environment</b>	Material	Recycling	MAR	EP
		Renewables	RMA	EP
	Energy	Efficiency	ENE	EP
	Water	Consumption	WAC	EQ/RL
		Discharge	WAD	EQ/RL
		Impact	WAI	EQ/RL
		Recycling	WAR	EQ/RL
	Biodiversity	Land	LAN	EQ/RL
		Habitat	HAB	EQ/RL
		Strategy	BDS	EQ/RL
	Emission, Effluent, and Waste	Spills	SPI	EP
		Habitat's report	HAR	EQ/RL
	Product & Service	Initiative	PSI	EQ/RL
		Packaging	PSP	EP
<b>Social</b>	Employment	Retention rate	EMR	EP
		Compliant	EMC	EP
		Demographic structure	EMD	EQ/RL
	Occupational health and safety	Workforce representation	WFR	EQ/RL
		Education	EDU	EQ/RL
	Training & education	Policy and procedures	POP	EQ/RL
	PSS labeling	Product information	PIN	EP
		Noncompliance records	NCR	EP

			Public trust	PUT	EP
			Marketing benefits	MAB	EP
			Non-compliance incidents	NCI	EP
Compliance with social standards			Values	SFI	EQ/RL
			Sanctions	SSA	EP
			Grievances	SGR	EQ/RL
Governance			Transparency	TRP	EP
			Corruption	COR	EQ/RL

## Key

Equal performance (EP) - Exclusion done based on equal performance and/or lack of direct data

Relevance (RL) - Exclusion based on relevance to the manufacturing of FS bracket manufacturing

### 6.4.2 Test case: Materials and methods

The manufacturing of Faceshield brackets used for this study has been done using three methods of manufacturing; injection molding (ALT<sub>1</sub>), 3D printing (ALT<sub>2</sub>), and laser cutting (ALT<sub>3</sub>). Each process is based on a specific application, material type, and requirements as it is applied to the manufacturing of the Faceshield bracket used for sustainability evaluation in this study. Analytic Hierarchy Process (AHP) is used for multicriteria decision analysis and aggregated evaluation of indicators which involves a definition of the decision tree, comparison judgment matrix, and calculation of aggregated criteria, subcriteria, sub-subcriteria, and alternatives.

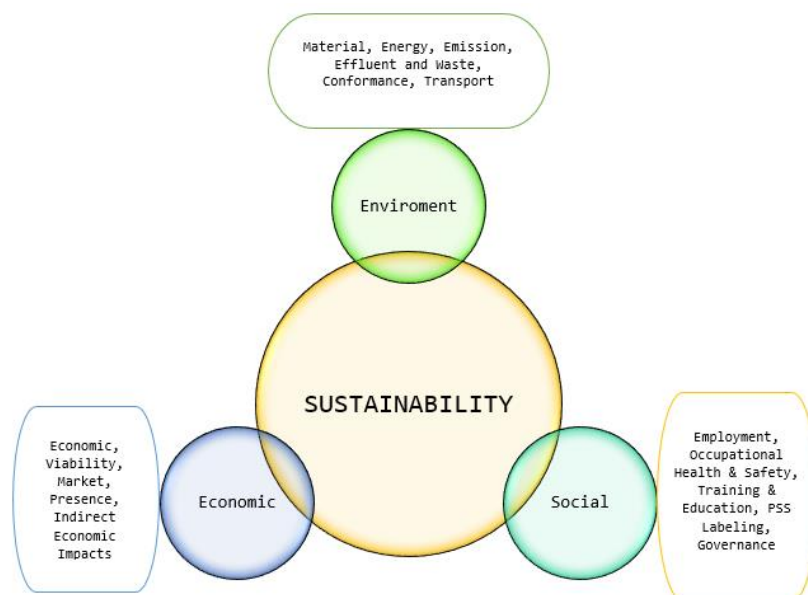


Figure 6.3 Sustainability pillars and selected subcriteria proposed for analysis

Sustainability assessment framework for sustainability performance of manufacturing processes proposed by (Saad et al., 2019) which mainly focuses only on product level and most relevant

sustainable performance indicators for utilized processes and product selected from a study by (Taddese et al., 2020) as shown in Figure 6.3 is utilized as input for this study.

#### **6.4.2.1 Injection molding**

Injection molding (first method, ALT<sub>1</sub>) requires a very large machine tool and a separate design of mold before manufacturing. It is implemented by specialized companies that have made significant investments because this process is based on a high technicality. The primary advantages of this method are the ability to produce a single bracket in 1.2 minutes (quickest) and help to manufacture a bracket with excellent surface finish and better mechanical property, which is cost-competitive for mass production. The obvious disadvantage is that it requires more time and is costly for modification since it requires design for a new mold. During this study, the design and manufacture of the molds required 3 days of work. Even a minor modification requires the same amount of time. The sustainability performance of injection molding is highly dependent on the raw material use, mold design, and associated process parameters to evaluate production rate, overall product cost, efficiency, and dimensional accuracy (Barbosa et al., 2018).

Some of the material portfolios include Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), Polypropylene (PP), Polybutylene terephthalate (PBT) (Singh and Verma, 2017). The important process parameters include melt temperature, injection and packaging time, cooling or holding time, and injection pressure (Barbosa et al., 2018; Singh and Verma, 2017). Based on variation in these parameters, the possibility of minimizing common defects such as warpage, shrinkage, surface waviness, roughness, and weld lines is possible. Moreover, the type of raw material, mold design, and proper processing variables will enable fast production, low cost, high efficiency, and dimensional accuracy of complex components. For example, as per (Elduque et al., 2018), a higher mold temperature is required during filling but a rapid cooling method is needed to decrease the molding cycle.

The environmental impact assessment of the use phase of the product is low due to a lack of life cycle inventory data. Electricity consumption during manufacturing could be a consideration to make. Concerning greenhouse gas emission (GHG), for 1 Kg of recycled PBT, the contribution is dominated by the raw materials (up to 45%) and followed by manufacturing (38%), secondary packaging (5%), transport (3%) and end of life stages (9%). This percentage varies based on the type of input material where recycled ones show a significant decrease (up to 24%) when manufacturing is done from 100% recycled content (Dormer et al., 2013).

According to a study by (Huang et al., 2017), by using an integrated techno-economic model intended to estimate lead time, lifecycle primary energy use, GHG emissions and cost of injection mold, potential savings of 12% to 60% lead time, 70% to 80% downtime, 3% to 5% primary energy, 4% to 7% GHG emissions, and 15% to 35% cost for distributed AM over CM through

the 1 million injection molding cycles (Huang et al., 2017). Plastic injection molding increases indirect carbon emissions due to high electricity consumption during manufacturing (Rajemi and Hassan, 2015). The energy consumption of injection molding machines varies based on different parameters. This is taken as a reason for a higher cost and increased emission.

#### **6.4.2.2 3D printing**

The second method (ALT<sub>2</sub>) is 3D printing which results in a very light, very flexible with relatively lesser mechanical property than Faceshield bracket manufactured by injection molding. A major advantage, since manufacturing is directly done from the CAD model, it is the cheapest to manufacture as well as to modify, intermediate rigidity, better flexibility to fit into different face shapes and sizes. The disadvantage is that it takes the longest time (140 minutes for a single bracket) and it is convenient for small-scale production.

Generally, 3D printing is a fused deposition modeling (FDM) or fused filament fabrication (FFF) technique where a heated nozzle melts thermoplastic materials. A solid thermoplastic filament is forced through a heated extrusion nozzle, melted, and deposited to form objects for various applications in industrial or medical parts (Azimi et al., 2016; Bravi et al., 2019; Byrley et al., 2020; Davis et al., 2019).

The most common filament materials used by 3D printing for layer-by-layer object building include Polylactic acid (PLA), thermoplastic polyurethane (TPU), Nylon, ABS, and PC which can often be mixed with coloring dye and other additives (Davis et al., 2019). PLA is a biodegradable, corn-based plastic that prints at nozzle temperatures of up to 180°C and base plate temperatures near room temperature. But it would go up to 220°C and 80°C respectively for ABS because it is a stronger thermoplastic. According to (Bravi et al., 2019), Feedstock origin, nozzle, and baseplate temperatures during operation are the primary differences between ABS and PLA-based printers.

PLA, as a thermoplastic material, possesses behaviors in general packaging use and consumer products that are lightweight, require low processing temperature as compared to metal and glasses as well as good printability, sealable and ease of formability (Lim et al., 2008). Biodegradable thermoplastic is derived from renewable plant resources such as starch and sugar. Laser cutting of PLA can be performed with either a 9.3 or 10.6-micron CO<sub>2</sub> laser. Laser cutting of PLA creates a clean, smooth edge without discoloration and depth with a clean colorless surface finish. As an advantage, PLA is compostable and derived from renewable sources, it helps to alleviate solid waste disposal problems and to lessen the dependence on petroleum-based plastics for packaging materials (Lim et al., 2008).

The primary advantage of the additive manufacturing method is enabling novel designs to solve manufacturing constraints. Moreover, advantages like material efficiency, modularity, and high automation. Last but not least, the requirement of fewer fixtures and tooling will greatly expand the economic viability of small-volume production and customization (Huang et al., 2017). But as a common disadvantage, (Byrley et al., 2020) reports that filament extruder emits large amounts of ultrafine respirable particles and various Volatile Organic Compounds (VOCs). The amount varies depending on operations. The heating process results in the emission of Volatile gases and ultrafine particles (UFPs) that deteriorate indoor air quality. This emission of VOC depends on specific types of filaments used based on the additives in each filament. For example, ABS was found to release more total VOC than PLA. Some VOCs possess toxic, irritant, and/or odorant properties. Operating indoors for hours and emission is released over a long time resulting in acute and chronic exposure to users and surrounding occupants.

According to (Davis et al., 2019; Khosravani and Reinicke, 2020), indoor operation of 3D printers are found to be sources of numerous VOCs and particles that can be released indoor air with 216 individual VOCs identified to impact indoor air and human health. Overall particle emission depends on filament material, extruder temperature, filament color, build plate heating, and printer model. For example, according to (Azimi et al., 2016), 3D printers emit ultrafine particles and VOCs. Emission of UFPs where particle dimensions are less than 100nm and hazardous VOCs varies depending on printer model, filament type, nozzle, bed temperature, and printing time. The VOCs emitted ABS ranges from 10 to 110µg/min and PLA from 4 to 5 µg/min.

#### **6.4.2.3 Laser cutting**

The third method (ALT<sub>3</sub>), laser cutting also uses a big machine bed and boards of PP. Even though the 3D printing took more time, this method takes 1.25 minutes for a single bracket, longer than injection molding and it is also convenient for small-scale production. Since laser cutting is established as Fab Lab, innovative designing and fabrication of parts can be done by individuals. It is a digital subtractive manufacturing technique from digital DXF files showing topographic information contained in a vector file and uses a laser power source that generates large amounts of energy to cut the material on the machine bed.

Necessary input information before the operation is the pattern (topographic information), material type, size (thickness, shape). The process allows cutting thin sheets of different materials. Depending on the dimensions of the plate, a large number of parts can be produced at the same time without human intervention. Depending on the material, smoke may be produced. This process is easy to access, as it uses common resources that are easily shared. The investment cost of an entry-level machine is quite low (between 10 and 30 k€). It should be noted that the use of this process required a redesign of the part and a simplification of the shapes. The purpose of this simple redesign is to transform a 3D part into a set of 2D parts

assembled. The obtained part is lighter and less resistant. Thus, these characteristics place the accessibility of this process between injection molding and 3D printing.

Thus, we compare three processes with very different characteristics: one very industrial process and two processes for the general public. Indeed, the question of the dissemination of the means of production is important within the framework of Industry 4.0.

Table 6.5 Important feature of the three processes

Feature	Injection Molding	3D Printing	Laser Cutting
Material	PP	PLA	PP
Material Format	Pellet	Filament	Plate
Material Cost	2,13 €/ Kg	30 € / Kg	5,88 € /g
Weight / part	36 g	32 g	13 g
Waste / part	0 g	4 g	1,5 g
Manufacturing time	1 min 12 s / part	140 minutes / part	1 min 25 s / part
Machine Cost	20 € / h	1 € / h	5 € / h
Energy consumption	500 Wh	375 Wh	52 Wh
Skill	Important Operator training 3 days Technician training 1 year	Weak	Medium Operator training 30 min Technician training 2 days
Investment	Need an industrial infrastructure of large machine tool	There is no need for infrastructure	a structure like Fab Lab has to be developed

Table 6.5 represents selected important features for the three processes. These features were utilized to assist decision-makers to make judgments in alternative comparisons where judgments associated with the material utilized, product weight, manufacturing time, cost, and required training for skill enhancement. Though few selected features are reported in this table, the decision-making process for the entire sub-subcriteria involved categorized comparison for each of the three processes depends on relevant information gathered for each process and Faceshield manufactured as reported in Appendix A.

### 6.4.3 Criteria contributions to each sustainability dimension

This section summarizes approaches and definitions on the selection and contribution of each subcriteria to the three dimensions of sustainability. This is categorized as a subcriteria contribution to environment, economic and social dimensions, respectively.

#### 6.4.3.1 Subcriteria contribution to Environmental dimension

##### 1. Material (SC<sub>1</sub>)

The contribution of the material in this study is structured based on material consumption (SSC<sub>1</sub>), material efficiency (SSC<sub>2</sub>), availability (SSC<sub>3</sub>), and recovery of material (SSC<sub>4</sub>). Material

consumption refers to the total amount of material consumed to manufacture a single Faceshield bracket, which is approximated from the total weight of the bracket manufactured through each of the three processes. The efficiency of material utilization is done by subtracting the weight of the bracket from the total weight of raw material purchased. Currently, since there is no recycling, the possibility of determining/planning for recycling will help existing waste to reenter the system to have better material efficiency. This means material efficiency can still be enhanced by introducing recycling. Material availability has also been assessed. The raw materials used are propylene (PP) and Polylactic acid (PLA). The raw materials allow easy implementation, faster molding and printing, and lesser waste. PP is applied for injection molding and laser cutting and PLA is applied for 3D printing to manufacture the bracket. But various alternatives to replace these materials include ABS, PETG, TPU95, etc. depending on the manufacturing method and application.

## **2. Energy (SC<sub>2</sub>)**

The contribution to energy is determined based on energy consumption (SSC<sub>5</sub>) and utilization of renewable energy (SSC<sub>6</sub>). Energy consumption can be considered as direct and indirect. In the manufacturing of the Faceshield bracket, energy is consumed in material extraction, processing, and transportation (which was not addressed in this study) but approximated consumption of energy consumption by machine is considered. To manufacture a single bracket, 3D printing uses a 150W machine and runs for 2.5 hours and power consumption of approximately 0.375 KWh and a laser cutter uses a laser tube (150W) with a total power of 2.5KW, resulting in energy consumption of 0.052 KWh. Thus, energy consumptions of machine operation and material heating are of major interest. As an initiative for energy-efficient production, there is a high chance of utilizing a recycled PP and PLA, instead of virgin input, as a means to minimize direct and indirect energy consumption.

## **3. Emission, Effluent, and Waste (SC<sub>3</sub>)**

The effect of EEW is connected with machines utilized, transportation, and mechanism of disposal (Beng and Omar, 2014; Chatzisideris et al., 2016; Deutz et al., 2013; Dufrene et al., 2013; Giffi et al., 2014). The manufacturing sector contributed 19% of the GHG emission (2013) in the economic activity of European countries (Saad et al., 2019). Thus, advancements in technologies are helping a minimized impact associated with EEW through minimized energy and resource consumption. Contributions of Greenhouse gases (GHG) emission (SSC<sub>7</sub>), primary air pollutants, PAPs (SSC<sub>8</sub>) secondary air pollutants, SAPs (SSC<sub>9</sub>), and waste (SSC<sub>10</sub>) are considered in this category mainly associated with machines utilized, transportation, and disposal mechanisms. The manufacturing sector contributed 19% of the GHG emission (2013) in the economic activity of European countries (Saad et al., 2019). Thus, advancements in technologies are helping a minimized impact through minimized energy and resource



consumption. In the manufacturing of the bracket, a process-level GHG emission often occurs during material heating and extrusion, where the contribution to GHG emission is less as compared to raw material treatment, transportation, and compression. According to a study by (Maga et al., 2019), the conversion of methane ( $\text{CH}_4$ ) is less than 0.1% and leads to neither significant emission of GHG nor energy savings and contributions during treatment, transportation is more than extrusion and recycling of PLA results in minimizing GHG emission.

PAPs are contributed as direct emissions such as  $\text{CO}_2$ ,  $\text{SO}_x$ , CO and PM, VOC, etc., and SAPs such as smog,  $\text{SO}_2$  and other pollutants from NOX and VOCs. heating of PLA to a temperature greater than  $200^\circ\text{C}$  may be harmful to human health and more than 216 individual VOCs are released into the indoor air (Bravi et al., 2019; Davis et al., 2019). In injection molding, volatile emissions occur from the vents in heating or injection cylinders and molds. According to (Azimi et al., 2016), the highest processing and decomposition temperatures for PP are  $275^\circ\text{C}$  and  $300^\circ\text{C}$  respectively but decomposition products are not forming at or near injection molding temperature. For reference, the VOCs emitted ABS and HIPS range from 10 to  $110\mu\text{g}/\text{min}$  and PLA from 4 to  $5\mu\text{g}/\text{min}$  (Azimi et al., 2016). The Injection molding process generates high environmental emissions during high temperature melting and in 3D printing during extrusion of the filament within the melting temperature ranges of  $200^\circ\text{C}$  to  $318^\circ\text{C}$  for PP. The selection of the filament material is an indicator for potential VOCs that would impact human health and working conditions such as proper ventilation in case of laser cutting of plastics may minimize the impact on the operators.

Concerning waste, for manufacturing using injection molding, there is no waste. But there is an advantage of reusing wastes of PP from injection molding which will significantly minimize the contribution of waste to the environment. The materials used in all three processes are recyclable and waste generation is limited, approximately 4g for 3D printing and 1.5g for laser cutting per Faceshield bracket. Moreover, the initiative to mitigate environmental impacts can be achieved more through energy-saving especially in the preparation and transportation of raw material.

#### **4. Conformance ( $\text{SC}_4$ )**

Conformance is measured through monetary values of fines for non-compliance ( $\text{SSC}_{11}$ ), the number of nonmonetary sanctions ( $\text{SSC}_{12}$ ) for noncompliance with environmental regulations, and total environmental protection expenditures and investment ( $\text{SSC}_{13}$ ). There is a variation among the two processes concerning compliance to social standards (Behrisch et al., 2011; Beng and Omar, 2014; Cor et al., 2014; Deutz et al., 2013). There is a good trend that PLA is made from renewable sources and contributes less to negative impacts to the environment and less chance for nonmonetary fines or sanctions during processing. Moreover, post-use processing could be possible through recycling for both processes.

**5. Transport (SC<sub>5</sub>)**

Transport considers contributions from the environmental impact of transporting products (SSC<sub>14</sub>) and strategy of introducing efficient transportation mode (SSC<sub>15</sub>). A 3D printing device can be implemented locally and make manufacturing closer to users of products which significantly shorten supply chains and cut down logistics and transportation costs in CM (Badurdeen and Jawahir, 2017; Behrisch et al., 2011; Bereketli and Erol Genevois, 2013; Cobut et al., 2015; Cor et al., 2014; Deutz et al., 2013).

Environmental impact associated with transportation includes material and raw materials. The high infrastructure need in injection molding demands transportation of raw material to manufacturing site and manufactured products to users which leaves this impact higher than 3D printing which can be located either consumer or near the material source. Thus, at the costs of establishing infrastructures and Fab Labs, there is also a possibility of considering energy-efficient transportation near the user or material source.

**6.4.3.2 Subcriteria contribution to Economic dimension****1. Economic viability (SC<sub>6</sub>)**

This considers contributions from a direct economic value (SSC<sub>16</sub>) generated, cost (SSC<sub>17</sub>) incurred throughout the product's life cycle, innovation (SSC<sub>18</sub>) as expenditure on research and development, and benefit plans (SSC<sub>19</sub>) such as possible financial assistance from the government or other sources. The value of the product can be seen from different perspectives or the possibility of including relevant features such as variations on thickness, weight, etc., and the possibility of enhancing features related to compatibility in size and shape and mechanical property. Evaluation can be given in these aspects of weight, thickness, size, shape, and property. The economic value of the bracket manufactured through these three processes depends on the scale of production. The high economic value of bracket goes to injection molding followed by laser cutting than for 3D printing where this is economically valuable for small scale production. The 3D printing facility provides a higher chance for innovation and there is a chance of getting financial assistance from the government.

**2. Marketing presence (SC<sub>7</sub>)**

The contribution to marketing presence is considered from standard entry-level wages (SSC<sub>20</sub>), spending policy on locally-based suppliers (SSC<sub>21</sub>), and hiring from the local community (SSC<sub>22</sub>). It is a bit difficult to spend on locally-based suppliers for manufacturing using injection molding. But if considering material development, PLA production using fermentation process can engage many local raw material suppliers. Moreover, it is economically beneficial to center distribution nearby suppliers which will minimize costs and time spent in transportation to reach customers.

### **3. Indirect economic impact (SC<sub>8</sub>)**

The indirect economic impact is measured through investment (SSC<sub>23</sub>) and service primarily for public benefit and impact knowhow (SSC<sub>24</sub>) towards job creations by suppliers, increasing productivity and business to business activity. AM helps to produce customized or parts with multiple integrated components for better commercial benefit. Encourages entrepreneurship and product development by minimizing barriers due to the ease of producing a prototype just by printing in equipment rather than requiring a factor setup. Encourage to create personalized products by just using 3D printers to test the customized products (Badurdeen and Jawahir, 2017; Vereinte Nationen, 2007).

Injection molding needs an industrial infrastructure of large machine tools which could benefit the public through commercial, in-kind, or pro-bono, or public good engagement. But this is more expensive than a laser cutting facility that needs the development of structure like Fab Lab as compared to the least expensive 3D printing where there is no need for infrastructure development. Unlike injection molding which is economically beneficial in mass production, 3D printing will contribute less in economic impacts such as in jobs created by suppliers, productivity enhancement, and business-to-business activity.

#### **6.4.3.3 Subcriteria contribution to Social dimension**

##### **1. Employment (SC<sub>9</sub>)**

The type of process will have an impact on the type and required performance of manpower as an employee (Chaim et al., 2018; Esty et al., 2005; Ghobadian et al., 2018; Holm, 2018; Zackrisson et al., 2017). Thus, contribution to employment is determined from total workforce employment type (SSC<sub>25</sub>), new employee hires and turnover as job creation (SSC<sub>26</sub>), workforce safety and comfort through job security (SSC<sub>27</sub>), and performance (SSC<sub>28</sub>) based on employees skill, knowledge and competences.

The manufacturing of brackets doesn't require various employment types besides basic part design and machine operation. But since sustainability issues consider lifetime aspects, the growing market opportunities of PLA and PP thermoplastic materials will involve various types. Thus, job creation and accessibility to the labor market are bright in applications using these materials. Moreover, according to estimates of European Bioplastics, by 2030, 300,000 highly skilled jobs will be created in the European bio-market, more than 10 times its current numbers.

Concerning human safety due to the emission of harmful chemicals, the process-related effect due to material used for human safety (operator) is not a problem as far as manufacturing is done within proper ventilation. With poor ventilation, fumes from laser cutting of plastics affect

machine operators. For the three processes, employee performance can be easily enhanced through operator and technician training limited to few days. It is also possible to enhance through self-learning such as in 3D printing.

## **2. Occupational health and safety (SC<sub>10</sub>)**

Major contributors considered for occupational health and safety (OHS) are injury rate (SSC<sub>29</sub>) as acute injuries, lost working days, and illness incident and education (SSC<sub>30</sub>) for prevention and risk control programs. The injury rate is significantly minimized in additive manufacturing methods since there is no continuous involvement of workers while processing and post-processing activities (Bereketli and Erol Genevois, 2013; Borchardt et al., 2011; Cohen et al., 2014; Eastwood and Haapala, 2015; Shojaeipour, 2015; Yuan et al., 2012). Thus, there is a minimized possibility of injury rate or work-related fatalities in 3D printing and laser cutting as compared to injection molding, which has shown a growing injury rate even with experienced workers mainly related to training and disregarding safety issues such as proper spacing, lighting, cleaning, etc. Thus, higher training and education are needed for injection molding for safety and better skill enhancement training for 3D printing to boost innovation.

## **3. Training and education (SC<sub>11</sub>)**

Average hours of training needed (SSC<sub>31</sub>), skill management programs for enhanced career development (SSC<sub>32</sub>), and regular performance and development reviews (SSC<sub>33</sub>) are contributions analyzed for this subcriteria of the social dimension. Realization of the intended product requires training and education for specific skill, knowledge, or competence enhancement based on the type and total hour required depending on the type of manufacturing process. This is also related to continued employability and career development and it could be given through company or self-training.

## **4. Product and service labeling (SC<sub>12</sub>)**

Product and service (PSS) labeling considers customer satisfaction (SSC<sub>34</sub>) through safety, comfort, better value, conformity (SSC<sub>35</sub>) to customer needs and values (SSC<sub>36</sub>) for the monetary value of fines for non-compliance to provisions and use of PSS. Manufacturing can be closer to users and can easily be built locally rather than large factories and the level of quality or comfort expected by users depend on their needs but based on the type of process measure of flexibility in adaptation work is very relevant to measure.

## **5. Governance (SC<sub>13</sub>)**

The two contributions considered for governance are equity and fairness (SSC<sub>37</sub>) concerning equal rights and freedom and efficiency (SSC<sub>38</sub>) or the performance of an employee or a team. In raw material (PLA) development for 3D printing, there is a moral issue of spending on crops for bioplastics where there are many who require it for food. But the ease of self-learning, cheaper price, and printing flexibility show equal rights and freedom for innovation and product manufacturing. As a method of enhancing the performance of an employee in a day, training in the company for injection molding and laser cutting but self-training for 3D printers is an opportunity to take.

### **6.4.4 Structuring the problem**

As reported in section 6.4.2, criteria and subcriteria contributions to each dimension of sustainability are identified and reported. The indicators' tree categorizes the problem starting from the goal/objective of sustainability represented at the highest level until the contributions to the lowest level. The cumulative effect of sub-subcriteria from the lowest level will be reflected in the goal. The three alternatives are shown in the lowest level of the hierarchy. This tree is reported in Figure 6.4. This indicator tree contains four hierarchical levels. First, the objective or goal of the problem is defined as assuring sustainability. Level 1 compares the three criteria (environment, economic and social dimensions) against the goal. Level 2 compares the selected subcriteria by compared to criteria. Level 3 compares each sub-subcriteria to subcriteria and finally, level 4 contains the three alternatives connected to sub-subcriteria. The goal of each analysis is to target the best criterion and the best alternative compared to the level hierarchical superior.

Breakdown of the problem into the elements mentioned in the form of a hierarchical structure developed on four levels. Level 1 = C<sub>i</sub>, shows the criteria retained for this analysis which make up as follows: C<sub>1</sub> = environment, C<sub>2</sub> = economic, C<sub>3</sub> = social dimension. Level 2 = SC<sub>i</sub> contains the 5 sub-criteria of environment, 3 subcriteria of economic, and 5 subcriteria of the social dimension. Furthermore, level 3 = SSC<sub>i</sub> reports each sub-subcriteria corresponding to each subcriteria mentioned in level 2. The last and the fourth level represented the three alternatives (ALT<sub>i</sub>) of the manufacturing process, Injection molding (ALT<sub>1</sub>), 3D printing (ALT<sub>2</sub>), and laser cutting (ALT<sub>3</sub>).

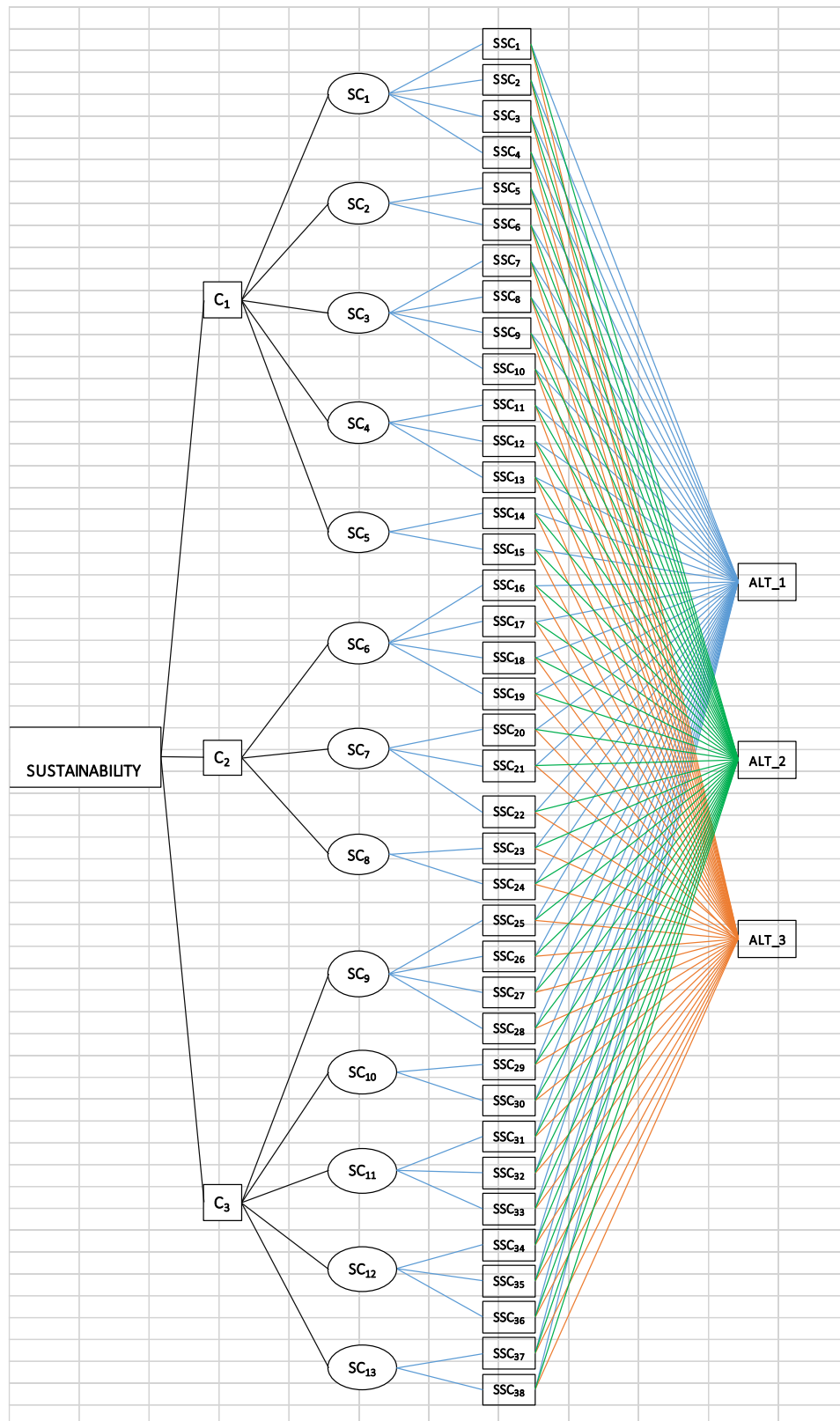


Figure 6.4 Indicators' tree - A four level hierarchy [proposed by authors]

## **6.4.5 AHP Analysis**

### **6.4.5.1 Approach**

The goal of this study is to evaluate the sustainability performance of three methods in the manufacturing of Faceshield brackets, selection of performance indicators is based on relevance to sustainability and chance of proper data gathering. The basis for judgment by decision-makers is already presented in section 6.4.3 based on data gathered from manufacturers and operators in conjunction with secondary data collected through literature about each process. The indicators' tree, Figure 6.4, shows splitting the problem in a hierarchy of criteria, subcriteria, and sub-subcriteria to simplify the overall evaluation. The first level contains 3 criteria, the second level contains 18 subcriteria and the third level contains 38 sub-subcriteria.

Furthermore, determination of comparison values for the three criteria ( $C_1$  to  $C_3$ ), the thirteen subcriteria ( $SC_1$  to  $SC_{13}$ ), the thirty-eight sub-subcriteria ( $SSC_1$  to  $SSC_{38}$ ), and the three alternatives ( $ALT_1$  to  $ALT_3$ ) has been done based on the fundamental comparison scale shown in Table 6.1. Three representative sub-subcriteria from each dimension of sustainability ( $SSC_1$ ,  $SSC_{17}$ , and  $SSC_{31}$ ) are picked to show how judgments on alternatives are made for selected SPI (sub-subcriteria).

1. *Material consumption ( $SSC_1$ ):* As mentioned in section 6.4.3, the material consumption is approximated from the total weight of Faceshield brackets. Thus, for  $SSC_1$ , decision-makers consider equal judgment for  $ALT_1$  and  $ALT_2$  since the weights of Faceshield manufactured by the two processes are 36g and 32g and showed not a big variation (intensity of importance falls within the range of equal importance). But as compared to these two processes, the Faceshield bracket manufactured by  $ALT_3$  weights 13g, which is the least weight, and for  $SSC_1$ , it is the preferred alternative for this sub-subcriteria than the two where the importance level from the comparison table shown in Table 6.3 is, strong importance for  $ALT_1$  and moderate importance for  $ALT_3$ .
2. *Economic cost ( $SSC_{17}$ ):* The judgment made on economic cost is based on the cost of each machine used for the three alternatives. As compared to  $ALT_1$ , the machine costs for  $ALT_3$  is lower and even very much lower for  $ALT_2$ . As per the information gathered,  $ALT_2$  costs about 3,000 euros and  $ALT_3$  costs about 15,000 euros. However, this doesn't mean there are an equivalent production rate and economic value of the Faceshield bracket, the initial economic cost is important for users. Therefore, based on this understanding,  $ALT_1$  is given a higher value than  $ALT_2$  and  $ALT_3$  with an intensity of importance 8 and 3 respectively. Whereas,  $ALT_3$  is given a value of strong importance (intensity of 5).

3. *Skill management* ( $SSC_{31}$ ): Average hours of training and education for specific skill, knowledge, or competence needed ( $SSC_{31}$ ) varies with the type and hour required depending on the type of manufacturing processes. Moreover, Table 6.5 represents that training is highly needed for  $ALT_1$  than  $ALT_3$  and  $ALT_2$  respectively. The training need for  $ALT_2$  is not that mandatory. Thus, based on this information, decision-makers preferred  $ALT_1$  with strong importance for  $ALT_2$  and moderate importance with  $ALT_3$ . Moreover,  $ALT_3$  is preferred over  $ALT_2$  with moderate importance.

#### 6.4.5.2 Criteria

AHP analysis is performed through step by step analysis of criteria, subcriteria, and sub-subcriteria for all four levels based on the procedures reported in section 6.2.1. The criteria for this specific problem, there are three criteria, environment, economic and social aspects since the goal of the study is sustainability.

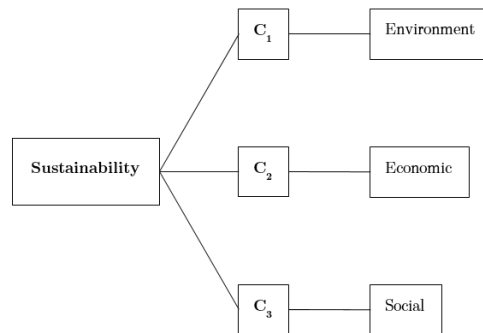


Figure 6.5 Criteria

#### 1. Pairwise comparison matrix analysis

Based on the hierarchical structure is defined and identification of criteria, subcriteria, and sub-subcriteria is done, pairwise comparison at each level is performed. For the sake of simplicity, this section and afterward abbreviations defined earlier will be utilized in Table 6.3. The comparisons will result in what is called a judgment matrix which is a numerical representation between two elements. These elements can be criteria, subcriteria, or sub-subcriteria depending on the level under consideration.

The first level consists of the three criteria of environment ( $C_1$ ), economic ( $C_2$ ), and social ( $C_3$ ), as represented in Figure 6.5 which is a cut part from the global indicators' tree represented in Figure 6.4. Thus, in this section, a binary comparison analysis is done by comparing relative importance to the objective of the three criteria. The objective is sustainability. Relative importance is expressed based on scales called Saaty's fundamental comparison scale as shown in Table 6.1. This scale has been validated for its effectiveness in many applications as well as



through theoretical justifications. The numerical values represent the intensity of importance on a scale, 0-9.

Table 6.6 Comparison table (Criteria)

Goal	Comparison	Preference	Importance	Evaluation
Sustainability	C <sub>1</sub> / C <sub>2</sub>	C <sub>2</sub>	Weak	1/2
	C <sub>1</sub> / C <sub>3</sub>	C <sub>1</sub> /C <sub>3</sub>	Equal	1
	C <sub>2</sub> / C <sub>3</sub>	C <sub>2</sub>	Weak	2

The values of the comparison table in Table 6.6 are transformed into a judgment matrix shown below.

	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>
C <sub>1</sub>	1	1/2	1
C <sub>2</sub>	2	1	2
C <sub>3</sub>	1	1/2	1

## 2. Priority vector

The priority vector is determined first by performing sums of each column of the judgment matrix of the criteria and by then by dividing each element of the matrix by the column total and calculating the average of the elements of each row of the matrix (priority vector). The result is reported in Table 6.7. Finally, the maximum eigenvalue is calculated based on the priority vector.

Table 6.7 Priority vector (Criteria)

	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	Priority vector
C <sub>1</sub>	0.25	0.25	0.25	0.250
C <sub>2</sub>	0.50	0.50	0.50	0.500
C <sub>3</sub>	0.25	0.25	0.25	0.250

### a) Calculation of maximum eigenvalue ( $\lambda_{\max}$ )

The maximum eigenvalue determination is done using excel. The judgment matrix which is transformed from the criteria comparison in Table 6.6 is multiplied by the eigenvalue of the priority vector (n), the average of the values found is calculated. The result is called  $\lambda_{\max}$  value. Thus,  $a_{ij}$  as the judgment matrix of the value of the element (i) of the i<sup>th</sup> line and the element (j) in the j<sup>th</sup> column.

$$\lambda_{\max} = a_{ij} \frac{W_j}{W_i}$$

Where  $W_i$  = the contribution to the selection of the best choice and each of the criteria and  $W_j$  = the contribution of the specific criteria to the main objective. Thus, by following these steps, the maximum eigenvalue obtained is  $\lambda_{\max}=3$

### 3. Consistency verification

The measure of consistency checks the consistency of the judgments. The consistency index (CI) of a comparison matrix is also known as the variance of error incurred in estimating  $a_{ij}$ . It is computed as the ratio of the difference between the maximum eigenvalue minus the matrix size and the matrix size minus one as shown in equation 6.6. Therefore, the consistency index is then calculated for matrix size of 3 and maximum eigenvalue of 3 as,

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{3.00 - 3}{3 - 1} = 0$$

The consistency ratio (CR) is obtained by comparing the CI, with an appropriate number from the set of numbers reported in Table 6.4. These indexes are determined from a sample of randomly generated reciprocal matrices using the scales 1/9, 1/8... 8, 9. As a means of verification for consistency, if this ratio is not less than 0.1, the problem must be studied again and judgments have to be revised and must be first labeled as the first judgment is not consistent. In other words, a consistency index of 10% or less implies that the adjustment is small compared to the actual values of the eigenvector entries. Once the consistency ratio is determined, the consistency index (CI) is determined using Equations 6.6 and 6.7 as;

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{3.0803 - 3}{3 - 1} = 0.04$$

For n=3, RI = 0.52 read from Table 6.4. Thus, RI = 0.52

$$CR = \frac{CI}{RI} = \frac{0}{0.52} = 0$$

Verification: Since  $CR \leq 10\%$ , the degree of consistency is *Acceptable*.

#### 6.4.5.3 Subcriteria

In this stage, consideration of subcriteria to each criterion is made. These subcriteria are 13 in number and are located in the second level of the indicator tree represented in Figure 6.4 for the three criteria, environment ( $C_1$ ), economic ( $C_2$ ), and social ( $C_3$ ). Thus, analysis is separately done for each of the three criteria.

## 1. Pairwise comparison

### Environment

This subcriteria consists of 5 subcriteria ( $SC_1$  to  $SC_5$ ) as shown in the hierarchical representation of Figure 6.6. The criteria comparison scale in Table 6.3 is utilized based on judgments based on experience and data collected. For  $n=5$ , a total of 10 comparisons are made.

$$No\ of\ Comparisons = \frac{n \times (n-1)}{2} = \frac{5 \times (5-1)}{2} = 10$$

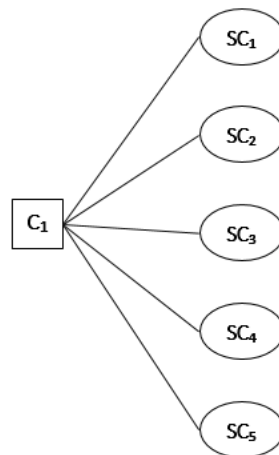


Figure 6.6 Subcriteria of Economic

### Economic

This subcriteria consists of 3 subcriteria as shown in the hierarchical representation of Figure 6.7. The criteria comparison scale in Table 6.3 is utilized based on judgments based on experience and real data collected. For  $n=3$ , a total of 3 comparisons are made.

$$No\ of\ Comparisons = \frac{n \times (n-1)}{2} = \frac{3 \times (3-1)}{2} = 3$$

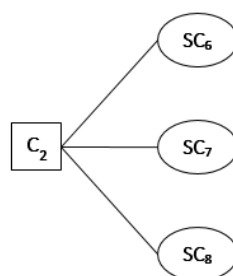


Figure 6.7 Subcriteria of Economic

### Social

This criterion consists of 5 subcriteria as shown in the hierarchical representation of Figure 6.8. The criteria comparison scale is reported in Table 6.1 based on experience and real data collected. For  $n=5$ , a total of 10 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{5 \times (5-1)}{2} = 10$$

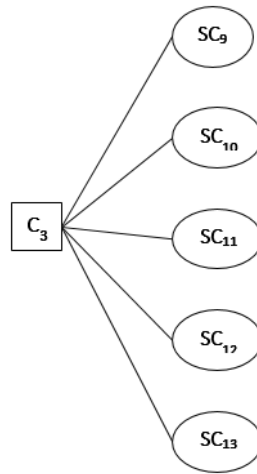


Figure 6.8 Subcriteria of Social

Table 6.8 Criteria Comparison Table – Criteria

Goal	Comparison	Preference	Importance	Evaluation
C <sub>1</sub>	SC <sub>1</sub> / SC <sub>2</sub>	SC <sub>1</sub> /SC <sub>2</sub>	Equal	1
	SC <sub>1</sub> / SC <sub>3</sub>	SC <sub>1</sub>	Very, very strong	8
	SC <sub>1</sub> / SC <sub>4</sub>	SC <sub>1</sub>	Very, very strong	8
	SC <sub>1</sub> / SC <sub>5</sub>	SC <sub>1</sub>	Moderate plus	4
	SC <sub>2</sub> / SC <sub>3</sub>	SC <sub>2</sub>	Very, very strong	8
	SC <sub>2</sub> / SC <sub>4</sub>	SC <sub>2</sub>	Very, very strong	8
	SC <sub>2</sub> / SC <sub>5</sub>	SC <sub>2</sub>	Weak	2
	SC <sub>3</sub> / SC <sub>4</sub>	SC <sub>3</sub> /SC <sub>4</sub>	Equal	1
	SC <sub>3</sub> / SC <sub>5</sub>	SC <sub>5</sub>	Very strong	1/7
	SC <sub>4</sub> / SC <sub>5</sub>	SC <sub>5</sub>	Very strong	1/7
C <sub>2</sub>	SC <sub>6</sub> / SC <sub>7</sub>	SC <sub>6</sub>	Very strong	7
	SC <sub>6</sub> / SC <sub>8</sub>	SC <sub>6</sub>	Moderate plus	4
	SC <sub>7</sub> / SC <sub>8</sub>	SC <sub>8</sub>	Moderate	1/3
C <sub>3</sub>	SC <sub>9</sub> / SC <sub>10</sub>	SC <sub>9</sub> /SC <sub>10</sub>	Equal	1
	SC <sub>9</sub> / SC <sub>11</sub>	SC <sub>9</sub>	Moderate	3
	SC <sub>9</sub> / SC <sub>12</sub>	SC <sub>9</sub>	Strong	5
	SC <sub>9</sub> / SC <sub>13</sub>	SC <sub>9</sub>	Strong	5
	SC <sub>10</sub> / SC <sub>11</sub>	SC <sub>10</sub>	Moderate	3
	SC <sub>10</sub> / SC <sub>12</sub>	SC <sub>10</sub>	Strong plus	6
	SC <sub>10</sub> / SC <sub>13</sub>	SC <sub>10</sub>	Strong plus	6
	SC <sub>11</sub> / SC <sub>12</sub>	SC <sub>11</sub>	Strong	5
	SC <sub>11</sub> / SC <sub>13</sub>	SC <sub>11</sub>	Moderate	3
	SC <sub>12</sub> / SC <sub>13</sub>	SC <sub>12</sub>	Moderate	3

The criteria comparison tables are transformed into matrices of judgments which are developed by transcribing the judgmental values in Table 6.8 for the three dimensions of sustainability. The formula mentioned in section 6.2.1 relevant to the comparison judgment matrix applies for all. Judgment matrices for each of the three subcriteria are reported below.

	SC <sub>1</sub>	SC <sub>2</sub>	SC <sub>3</sub>	SC <sub>4</sub>	SC <sub>5</sub>
SC <sub>1</sub>	1	1	8	8	4
SC <sub>2</sub>	1	1	8	8	2
SC <sub>3</sub>	1/8	1/8	1	1	1/7
SC <sub>4</sub>	1/8	1/8	1	1	1/7
SC <sub>5</sub>	1/4	1/2	7	7	1

(a) Environment

	SC <sub>6</sub>	SC <sub>7</sub>	SC <sub>8</sub>
SC <sub>6</sub>	1	7	4
SC <sub>7</sub>	1/7	1	1/3
SC <sub>8</sub>	1/4	3	1

(b) Economic

	SC <sub>9</sub>	SC <sub>10</sub>	SC <sub>11</sub>	SC <sub>12</sub>	SC <sub>13</sub>
SC <sub>9</sub>	1	1	3	5	5
SC <sub>10</sub>	1	1	3	6	6
SC <sub>11</sub>	1/3	1/3	1	5	3
SC <sub>12</sub>	1/5	1/6	1/5	1	3
SC <sub>13</sub>	1/5	1/6	1/3	1/3	1

(c) Social

## 2. Priority vector

The priority vector is determined first by performing sums of each column of judgment matrices and then by dividing each element of the matrix by the column total and calculating the average of the elements of each row of the matrix (priority vector) for subcriteria. The result is reported in Table 6.9. The maximum eigenvalue is calculated for each criterion based on the priority vector determined and the result is reported in Table 6.10.

Table 6.9 Normalization and priority vector calculation (Subcriteria)

	SC <sub>1</sub>	SC <sub>2</sub>	SC <sub>3</sub>	SC <sub>4</sub>	SC <sub>5</sub>	Priority vector
SC <sub>1</sub>	0.400	0.364	0.320	0.320	0.549	0.391
SC <sub>2</sub>	0.400	0.364	0.320	0.320	0.275	0.336
SC <sub>3</sub>	0.050	0.045	0.040	0.040	0.020	0.039
SC <sub>4</sub>	0.050	0.045	0.040	0.040	0.020	0.039
SC <sub>5</sub>	0.100	0.182	0.280	0.280	0.137	0.196

(a) Environmental criteria

	SC <sub>6</sub>	SC <sub>7</sub>	SC <sub>8</sub>	Priority vector
SC <sub>6</sub>	0.718	0.636	0.750	0.701
SC <sub>7</sub>	0.103	0.091	0.063	0.085
SC <sub>8</sub>	0.179	0.273	0.188	0.213

(b) Economic criteria

	SC <sub>9</sub>	SC <sub>10</sub>	SC <sub>11</sub>	SC <sub>12</sub>	SC <sub>13</sub>	Priority vector
SC <sub>9</sub>	0.366	0.375	0.398	0.288	0.278	0.341
SC <sub>10</sub>	0.366	0.375	0.398	0.346	0.333	0.364
SC <sub>11</sub>	0.122	0.125	0.133	0.288	0.167	0.167
SC <sub>12</sub>	0.073	0.063	0.027	0.058	0.167	0.077
SC <sub>13</sub>	0.073	0.063	0.044	0.019	0.056	0.051

(c) Social criteria

### 3. Consistency verification

Once again, the measure of consistency is calculated to know the consistency of judgments. A similar approach is followed as done in section 6.4.4.2. The matrix size is 5 for the environment, 3 for economic, and 5 for the social dimension with corresponding maximum eigenvalues of 5.277, 3.053, and 5.417 respectively. Therefore, the consistency index for each criterion is determined as shown in Table 6.10.

Table 6.10 Consistency verification (Subcriteria)

	Matrix size	Random Index (RI)	$\lambda_{\max}$	Consistency Index (CI)	Consistency Ratio (CR)	Verification CR <10%
Environment	5	1.11	5.277	$CI = \frac{5.277-5}{5-1} = 0.07$	$CR = \frac{0.07}{1.11} = 0.06$	Yes
Economic	3	0.52	3.053	$CI = \frac{3.053-3}{3-1} = 0.03$	$CR = \frac{0.03}{0.52} = 0.05$	Yes
Social	5	1.11	5.417	$CI = \frac{5.417-5}{5-1} = 0.10$	$CR = \frac{0.10}{1.11} = 0.09$	Yes

Verification: Since  $CR \leq 10\%$ , the degree of consistency is *Acceptable*.

#### 6.4.5.4 Sub-subcriteria

In this stage, considerations of sub-subcriteria to each subcriteria are analyzed. These sub-subcriteria are thirty-eight (38) in number and are located in the third level of the indicator tree represented in Figure 6.4 for the thirteen (13) subcriteria from SC<sub>1</sub> to SC<sub>13</sub>. Thus, analysis is separately done for each of the subcriteria as reported below.

#### 1. Pairwise comparison

##### Material (SC<sub>1</sub>)

For the first criteria, environment (C<sub>1</sub>), there are 5 subcriteria and 15 sub-subcriteria (SSC<sub>1</sub> to SSC<sub>15</sub>) as shown in the hierarchical representation of Figure 6.9. The criteria comparison scale in Table 6.3 is utilized to make judgments based on experience and data collected. For a matrix size of n=4, a total of 6 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{4 \times (4-1)}{2} = 6$$

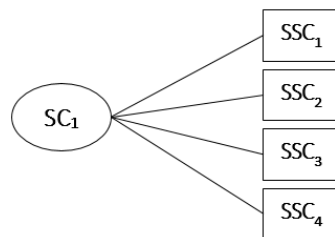


Figure 6.9 Sub-subcriteria of Material

### Energy (SC<sub>2</sub>)

Energy is one of the five subcriteria for the environmental criteria of sustainability. It contains two sub-subcriteria (SSC<sub>5</sub> and SSC<sub>6</sub>) as shown in Figure 6.10. For a matrix size of n=2, only one comparison is made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{2 \times (2-1)}{2} = 1$$

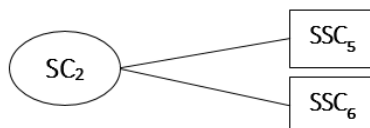


Figure 6.10 Sub-subcriteria of Energy

### Emission, effluent, and waste (SC<sub>3</sub>)

EEW is one of the five subcriteria for the environmental criteria of sustainability. This subcriteria contains four sub-subcriteria (SSC<sub>7</sub> and SSC<sub>10</sub>) as shown in Figure 6.11. For a matrix size of n=4, a total of 6 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{4 \times (4-1)}{2} = 6$$

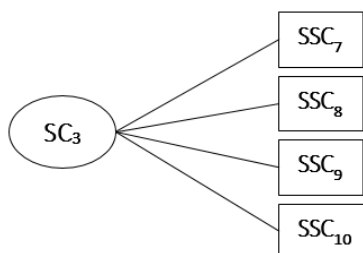


Figure 6.11 Sub-subcriteria of EEW

### Conformance (SC<sub>4</sub>)

Conformance is one of the five subcriteria for the environmental criteria of sustainability. This subcriteria contains three sub-subcriteria (SSC<sub>11</sub> and SSC<sub>13</sub>) as shown in Figure 6.12. For a matrix size of n=3, a total of 3 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{3 \times (3-1)}{2} = 3$$

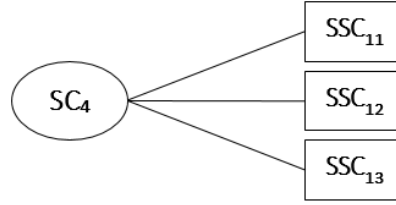


Figure 6.12 Sub-subcriteria of Conformance

**Transport (SC<sub>5</sub>)**

Transport is one of the five subcriteria for the environmental criteria of sustainability that contains two sub-subcriteria (SSC<sub>14</sub> and SSC<sub>15</sub>) as shown in Figure 6.13. For a matrix size of n=2, only one comparison is made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{2 \times (2-1)}{2} = 1$$

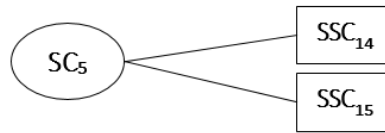


Figure 6.13 Sub-subcriteria of Transport

**Economic viability (SC<sub>6</sub>)**

Economic viability is one of the three subcriteria for the economic criteria of sustainability that contains four sub-subcriteria (SSC<sub>16</sub> and SSC<sub>19</sub>) as shown in Figure 6.14. For a matrix size of n=4, a total of 6 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{4 \times (4-1)}{2} = 6$$

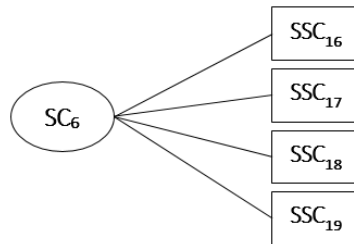


Figure 6.14 Sub-subcriteria of Economic viability

**Marketing presence (SC<sub>7</sub>)**

Marketing presence is one of the three subcriteria for the economic criteria of sustainability that contains three sub-subcriteria (SSC<sub>20</sub> and SSC<sub>22</sub>) as shown in Figure 6.15. For matrix size of n=3, a total of 3 comparisons are made.



$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{3 \times (3-1)}{2} = 3$$

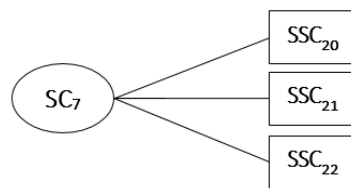


Figure 6.15 Sub-subcriteria of Marketing Presence

### Indirect economic impact (SC<sub>8</sub>)

Indirect economic impact (IEI) is one of the three subcriteria for the economic criteria of sustainability. The subcriteria contains two sub-subcriteria (SSC<sub>23</sub> and SSC<sub>24</sub>) as shown in Figure 6.16. For a matrix size of n=2, only one comparison is made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{2 \times (2-1)}{2} = 1$$

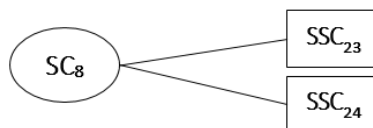


Figure 6.16 Sub-subcriteria of Indirect Economic Impact

### Employment (SC<sub>9</sub>)

Employment is one of the five subcriteria for the social criteria of sustainability. The subcriteria contains four sub-subcriteria (SSC<sub>25</sub> and SSC<sub>28</sub>) as shown in Figure 6.17. For a matrix size of n=4, a total of 6 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{4 \times (4-1)}{2} = 6$$

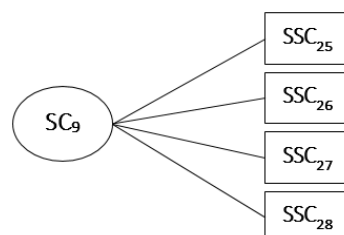


Figure 6.17 Sub-subcriteria of Employment

### Occupational health and safety (SC<sub>10</sub>)

OHS is one of the five subcriteria for the social criteria of sustainability that contains two sub-subcriteria (SSC<sub>29</sub> and SSC<sub>30</sub>) as shown in Figure 6.18. For a matrix size of n=2, only one comparison is made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{2 \times (2-1)}{2} = 1$$

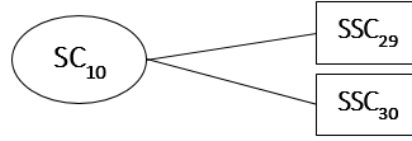


Figure 6.18 Sub-subcriteria of OHS

### Training and education (SC<sub>11</sub>)

Training and education are categorized as one of the five subcriteria for the social criteria of sustainability that contains three sub-subcriteria (SSC<sub>31</sub> and SSC<sub>33</sub>) as shown in Figure 6.19. For matrix size of n=3, a total of 3 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{3 \times (3-1)}{2} = 3$$

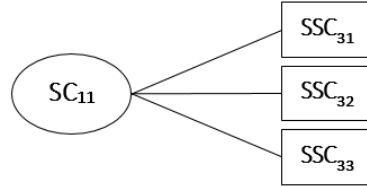


Figure 6.19 Sub-subcriteria of Training and education

### Product and service labeling (SC<sub>12</sub>)

It is one of the five subcriteria for the social criteria of sustainability. It contains three sub-subcriteria (SSC<sub>34</sub> and SSC<sub>36</sub>) as shown in Figure 6.20. For matrix size of n=3, a total of 3 comparisons are made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{3 \times (3-1)}{2} = 1$$

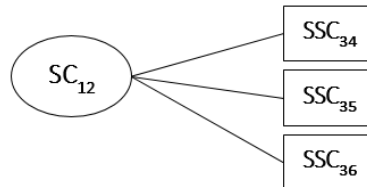


Figure 6.20 Sub-subcriteria of PSS labeling

### Governance (SC<sub>13</sub>)

Governance is one of the five subcriteria for the social criteria of sustainability that contains two sub-subcriteria (SSC<sub>37</sub> and SSC<sub>38</sub>) as shown in Figure 6.21. For the matrix size of n=2, only one comparison is made.

$$\text{No of Comparisons} = \frac{n \times (n-1)}{2} = \frac{2 \times (2-1)}{2} = 1$$

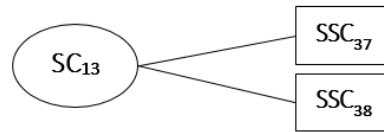


Figure 6.21 Sub-subcriteria of Government

## 1. Pairwise comparison

Relative importance is expressed based on Saaty's fundamental comparison scale as shown in Table 6.1. The numerical values represent the intensity of importance on a scale, 0-9.

Table 6.11 Sub-subcriteria comparison table for all dimensions

Subcriteria	Comparison	Preference	Importance	Evaluation
SC <sub>1</sub>	SSC <sub>1</sub> / SSC <sub>2</sub>	SSC <sub>1</sub>	Moderate	3
	SSC <sub>1</sub> / SSC <sub>3</sub>	SSC <sub>1</sub>	Moderate	3
	SSC <sub>1</sub> / SSC <sub>4</sub>	SSC <sub>1</sub>	Weak	2
	SSC <sub>2</sub> / SSC <sub>3</sub>	SSC <sub>2</sub>	Moderate	3
	SSC <sub>2</sub> / SSC <sub>4</sub>	SSC <sub>4</sub>	Moderate	1/3
	SSC <sub>3</sub> / SSC <sub>4</sub>	SSC <sub>4</sub>	Moderate plus	1/4
SC <sub>2</sub>	SSC <sub>5</sub> / SSC <sub>6</sub>	SSC <sub>5</sub>	Weak	2
SC <sub>3</sub>	SSC <sub>7</sub> / SSC <sub>8</sub>	SSC <sub>7</sub>	Moderate	3
	SSC <sub>7</sub> / SSC <sub>9</sub>	SSC <sub>7</sub>	Strong	5
	SSC <sub>7</sub> / SSC <sub>10</sub>	SSC <sub>10</sub>	Moderate plus	1/4
	SSC <sub>8</sub> / SSC <sub>9</sub>	SSC <sub>8</sub>	Moderate	3
	SSC <sub>8</sub> / SSC <sub>10</sub>	SSC <sub>10</sub>	Strong plus	1/6
SC <sub>4</sub>	SSC <sub>9</sub> / SSC <sub>10</sub>	SSC <sub>10</sub>	Very, very strong	1/8
	SSC <sub>11</sub> / SSC <sub>12</sub>	SSC <sub>12</sub>	Moderate	1/3
	SSC <sub>11</sub> / SSC <sub>13</sub>	SSC <sub>13</sub>	Moderate plus	1/4
SC <sub>5</sub>	SSC <sub>12</sub> / SSC <sub>13</sub>	SSC <sub>13</sub>	Moderate	1/3
	SSC <sub>14</sub> / SSC <sub>15</sub>	SSC <sub>15</sub>	Strong	1/5
SC <sub>6</sub>	SSC <sub>16</sub> / SSC <sub>17</sub>	SSC <sub>17</sub>	Weak	1/2
	SSC <sub>16</sub> / SSC <sub>18</sub>	SSC <sub>16</sub>	Weak	2
	SSC <sub>16</sub> / SSC <sub>19</sub>	SSC <sub>19</sub>	Moderate	1/3
	SSC <sub>17</sub> / SSC <sub>18</sub>	SSC <sub>17</sub>	Weak	2
	SSC <sub>17</sub> / SSC <sub>19</sub>	SSC <sub>19</sub>	Weak	1/2
SC <sub>7</sub>	SSC <sub>18</sub> / SSC <sub>19</sub>	SSC <sub>19</sub>	Moderate plus	1/4
	SSC <sub>20</sub> / SSC <sub>21</sub>	SSC <sub>20</sub>	Moderate plus	4
	SSC <sub>20</sub> / SSC <sub>22</sub>	SSC <sub>20</sub>	Weak	2
SC <sub>8</sub>	SSC <sub>21</sub> / SSC <sub>22</sub>	SSC <sub>22</sub>	Moderate plus	1/4
	SSC <sub>23</sub> / SSC <sub>24</sub>	SSC <sub>23</sub>	Moderate	3
SC <sub>9</sub>	SSC <sub>25</sub> / SSC <sub>26</sub>	SSC <sub>26</sub>	Weak	1/2
	SSC <sub>25</sub> / SSC <sub>27</sub>	SSC <sub>27</sub>	Moderate plus	1/4
	SSC <sub>25</sub> / SSC <sub>28</sub>	SSC <sub>25</sub>	Equally	2
	SSC <sub>26</sub> / SSC <sub>27</sub>	SSC <sub>27</sub>	Weak	1/2
	SSC <sub>26</sub> / SSC <sub>28</sub>	SSC <sub>26</sub>	Moderate plus	4
SC <sub>10</sub>	SSC <sub>27</sub> / SSC <sub>28</sub>	SSC <sub>27</sub>	Very strong	7
	SSC <sub>29</sub> / SSC <sub>30</sub>	SSC <sub>29</sub>	Moderate	3

SC <sub>11</sub>	SSC <sub>31</sub> / SSC <sub>32</sub>	SSC <sub>31</sub>	Moderate	3
	SSC <sub>31</sub> / SSC <sub>33</sub>	SSC <sub>31</sub>	Weak	2
	SSC <sub>32</sub> / SSC <sub>33</sub>	SSC <sub>33</sub>	Weak	1/2
SC <sub>12</sub>	SSC <sub>34</sub> / SSC <sub>35</sub>	SSC <sub>34</sub>	Moderate	3
	SSC <sub>34</sub> / SSC <sub>36</sub>	SSC <sub>36</sub>	Weak	1/2
	SSC <sub>35</sub> / SSC <sub>36</sub>	SSC <sub>36</sub>	Moderate	1/3
SC <sub>13</sub>	SSC <sub>37</sub> / SSC <sub>38</sub>	SSC <sub>37</sub>	Weak	2

Table 6.11 reports sub-subcriteria comparison table for all subcriteria of the three dimensions. These values of comparison are transformed into judgment matrices as shown below.

1. Material (SC<sub>1</sub>)

SC <sub>1</sub>	SSC <sub>1</sub>	SSC <sub>2</sub>	SSC <sub>3</sub>	SSC <sub>4</sub>
SSC <sub>1</sub>	1	3	3	2
SSC <sub>2</sub>	1/3	1	3	1/3
SSC <sub>3</sub>	1/3	1/3	1	1/4
SSC <sub>4</sub>	1/2	3	4	1

2. Energy (SC<sub>2</sub>)

SC <sub>2</sub>	SSC <sub>5</sub>	SSC <sub>6</sub>
SSC <sub>5</sub>	1	2
SSC <sub>6</sub>	1/2	1

3. Emission, effluent and waste (SC<sub>3</sub>)

SC <sub>3</sub>	SSC <sub>7</sub>	SSC <sub>8</sub>	SSC <sub>9</sub>	SSC <sub>10</sub>
SSC <sub>7</sub>	1	3	5	1/4
SSC <sub>8</sub>	1/3	1	3	1/6
SSC <sub>9</sub>	1/5	1/3	1	1/8
SSC <sub>10</sub>	4	6	8	1

4. Conformance (SC<sub>4</sub>)

SC <sub>4</sub>	SSC <sub>10</sub>	SSC <sub>11</sub>	SSC <sub>13</sub>
SSC <sub>11</sub>	1	1/3	1/4
SSC <sub>12</sub>	3	1	1/3
SSC <sub>13</sub>	4	3	1

5. Transport (SC<sub>5</sub>)

SC <sub>5</sub>	SSC <sub>14</sub>	SSC <sub>15</sub>
SSC <sub>14</sub>	1	1/5
SSC <sub>15</sub>	5	1

6. Economic viability (SC<sub>6</sub>)

SC <sub>6</sub>	SSC <sub>16</sub>	SSC <sub>17</sub>	SSC <sub>18</sub>	SSC <sub>19</sub>
SSC <sub>16</sub>	1	1/2	2	1/3
SSC <sub>17</sub>	2	1	2	1/2
SSC <sub>18</sub>	1/2	1/2	1	1/4
SSC <sub>19</sub>	3	2	4	1

7. Marketing presence (SC<sub>7</sub>)

SC <sub>7</sub>	SSC <sub>20</sub>	SSC <sub>21</sub>	SSC <sub>22</sub>
SSC <sub>20</sub>	1	4	2
SSC <sub>21</sub>	1/4	1	1/4
SSC <sub>22</sub>	1/2	4	1

8. Indirect economic impact (SC<sub>8</sub>)

SC <sub>8</sub>	SSC <sub>23</sub>	SSC <sub>24</sub>
SSC <sub>23</sub>	1	3
SSC <sub>24</sub>	1/3	1

9. Employment (SC<sub>9</sub>)

SC <sub>9</sub>	SSC <sub>25</sub>	SSC <sub>26</sub>	SSC <sub>27</sub>	SSC <sub>28</sub>
SSC <sub>25</sub>	1	1/2	1/4	2
SSC <sub>26</sub>	2	1	1/2	4
SSC <sub>27</sub>	4	2	1	7
SSC <sub>28</sub>	1/2	1/4	1/7	1

10. Occupational health and safety (SC<sub>10</sub>)

SC <sub>10</sub>	SSC <sub>29</sub>	SSC <sub>30</sub>
SSC <sub>29</sub>	1	3
SSC <sub>30</sub>	1/3	1

11. Training and education (SC<sub>11</sub>)

SC <sub>11</sub>	SSC <sub>31</sub>	SSC <sub>32</sub>	SSC <sub>33</sub>
SSC <sub>31</sub>	1	3	2
SSC <sub>32</sub>	1/3	1	1/2
SSC <sub>33</sub>	1/2	2	1

12. Product and service labeling (SC<sub>12</sub>)

SC <sub>12</sub>	SSC <sub>34</sub>	SSC <sub>35</sub>	SSC <sub>36</sub>
SSC <sub>34</sub>	1	3	1/2
SSC <sub>35</sub>	1/3	1	1/3
SSC <sub>36</sub>	2	3	1

13. Governance (SC<sub>13</sub>)

SC <sub>13</sub>	SSC <sub>37</sub>	SSC <sub>38</sub>
SSC <sub>37</sub>	1	2
SSC <sub>38</sub>	1/2	1

Once the sum of each column of judgment matrices is done, the priority vector is computed by dividing each element of the matrix by the column total and calculating the average of elements of each row.

## 2. Priority vector

The priority vector is determined first by performing sums of each column of judgment matrices and by then by dividing each element of the matrix by the column total and calculating the average of the elements of each row of the matrix (priority vector) for sub-subcriteria. The result is reported in Table 6.12. Based on these values of the priority vector, the maximum eigenvalue is also calculated and reported in Table 6.13.

Table 6.12 Priority vectors for sub-subcriteria

### 1. Material (SC<sub>1</sub>)

SC <sub>1</sub>	SSC <sub>1</sub>	SSC <sub>2</sub>	SSC <sub>3</sub>	SSC <sub>4</sub>	Priority Vector
SSC <sub>1</sub>	0.462	0.409	0.273	0.558	0.425
SSC <sub>2</sub>	0.154	0.136	0.273	0.093	0.164
SSC <sub>3</sub>	0.154	0.045	0.091	0.070	0.090
SSC <sub>4</sub>	0.231	0.409	0.364	0.279	0.321

### 2. Energy (SC<sub>2</sub>)

SC <sub>2</sub>	SSC <sub>5</sub>	SSC <sub>6</sub>	Priority Vector
SSC <sub>5</sub>	0.667	0.667	0.667
SSC <sub>6</sub>	0.333	0.333	0.333

### 3. Emission, effluent, and waste (SC<sub>3</sub>)

SC <sub>3</sub>	SSC <sub>7</sub>	SSC <sub>8</sub>	SSC <sub>9</sub>	SSC <sub>10</sub>	Priority Vector
SSC <sub>7</sub>	0.181	0.290	0.294	0.162	0.232
SSC <sub>8</sub>	0.060	0.097	0.176	0.108	0.110
SSC <sub>9</sub>	0.036	0.032	0.059	0.081	0.052
SSC <sub>10</sub>	0.723	0.581	0.471	0.649	0.606

### 4. Conformance (SC<sub>4</sub>)

SC <sub>4</sub>	SSC <sub>10</sub>	SSC <sub>11</sub>	SSC <sub>13</sub>	Priority Vector
SSC <sub>11</sub>	0.125	0.077	0.158	0.120
SSC <sub>12</sub>	0.375	0.231	0.211	0.272
SSC <sub>13</sub>	0.500	0.692	0.632	0.608

### 5. Transport (SC<sub>5</sub>)

SC <sub>5</sub>	SSC <sub>14</sub>	SSC <sub>15</sub>	Priority Vector
SSC <sub>14</sub>	0.167	0.167	0.167
SSC <sub>15</sub>	0.833	0.833	0.833

6. Economic viability (SC<sub>6</sub>)

SC <sub>6</sub>	SSC <sub>16</sub>	SSC <sub>17</sub>	SSC <sub>18</sub>	SSC <sub>19</sub>	Priority Vector
SSC <sub>16</sub>	0.154	0.125	0.222	0.160	0.165
SSC <sub>17</sub>	0.308	0.250	0.222	0.240	0.255
SSC <sub>18</sub>	0.077	0.125	0.111	0.120	0.108
SSC <sub>19</sub>	0.462	0.500	0.444	0.480	0.471

7. Marketing presence (SC<sub>7</sub>)

SC <sub>7</sub>	SSC <sub>20</sub>	SSC <sub>21</sub>	SSC <sub>22</sub>	Priority Vector
SSC <sub>20</sub>	0.571	0.444	0.615	0.544
SSC <sub>21</sub>	0.143	0.111	0.077	0.110
SSC <sub>22</sub>	0.286	0.444	0.308	0.346

8. Indirect economic impact (SC<sub>8</sub>)

SC <sub>8</sub>	SSC <sub>23</sub>	SSC <sub>24</sub>	Priority Vector
SSC <sub>23</sub>	0.750	0.750	0.750
SSC <sub>24</sub>	0.250	0.250	0.250

9. Employment (SC<sub>9</sub>)

SC <sub>9</sub>	SSC <sub>25</sub>	SSC <sub>26</sub>	SSC <sub>27</sub>	SSC <sub>28</sub>	Priority Vector
SSC <sub>25</sub>	0.133	0.133	0.132	0.143	0.135
SSC <sub>26</sub>	0.267	0.267	0.264	0.286	0.271
SSC <sub>27</sub>	0.533	0.533	0.528	0.500	0.524
SSC <sub>28</sub>	0.067	0.067	0.075	0.071	0.070

10. Occupational health and safety (SC<sub>10</sub>)

SC <sub>10</sub>	SSC <sub>29</sub>	SSC <sub>30</sub>	Priority Vector
SSC <sub>29</sub>	0.750	0.750	0.750
SSC <sub>30</sub>	0.250	0.250	0.250

11. Training and education (SC<sub>11</sub>)

SC <sub>11</sub>	SSC <sub>31</sub>	SSC <sub>32</sub>	SSC <sub>33</sub>	Priority Vector
SSC <sub>31</sub>	0.545	0.500	0.571	0.539
SSC <sub>32</sub>	0.182	0.167	0.143	0.164
SSC <sub>33</sub>	0.273	0.333	0.286	0.297

12. Product and service labeling (SC<sub>12</sub>)

SC <sub>12</sub>	SSC <sub>34</sub>	SSC <sub>35</sub>	SSC <sub>36</sub>	Priority Vector
SSC <sub>34</sub>	0.300	0.429	0.273	0.334
SSC <sub>35</sub>	0.100	0.143	0.182	0.142
SSC <sub>36</sub>	0.600	0.429	0.545	0.525

13. Governance (SC<sub>13</sub>)

SC <sub>13</sub>	SSC <sub>37</sub>	SSC <sub>38</sub>	Priority Vector
SSC <sub>37</sub>	0.667	0.667	0.667
SSC <sub>38</sub>	0.333	0.333	0.333

### 3. Consistency verification

As mentioned earlier, the measure of consistency helps the decision-maker to know how consistent the judgments made are. A similar approach is followed as done in sections 6.4.4.2 and 6.4.4.3 for criteria and subcriteria to verify the consistency of judgment in sub-subcriteria. The size of the matrix ( $n$ ), random index values (RI), and maximum eigenvalues ( $\lambda_{\max}$ ) and verification results for consistency are reported in Table 6.13.

Table 6.13 Consistency verification (Sub-subcriteria)

Subcriteria	n	RI	$\lambda_{\max}$	Consistency Index (CI)	Consistency Ratio (CR)	Verification CR <10%
SC <sub>1</sub>	4	0.89	4.263	0.088	0.099	Yes
SC <sub>2</sub>	2	0.00	2.000	0.000	0.000	Yes
SC <sub>3</sub>	4	0.89	4.243	0.081	0.091	Yes
SC <sub>4</sub>	3	0.52	3.101	0.051	0.097	Yes
SC <sub>5</sub>	2	0.00	2.000	0.000	0.000	Yes
SC <sub>6</sub>	4	0.89	4.051	0.017	0.019	Yes
SC <sub>7</sub>	3	0.52	3.000	0.034	0.066	Yes
SC <sub>8</sub>	2	0.00	2.000	0.000	0.000	Yes
SC <sub>9</sub>	4	0.89	4.003	0.001	0.001	Yes
SC <sub>10</sub>	2	0.00	2.000	0.000	0.000	Yes
SC <sub>11</sub>	3	0.52	3.011	0.006	0.011	Yes
SC <sub>12</sub>	3	0.52	3.065	0.033	0.063	Yes
SC <sub>13</sub>	2	0.00	2.000	0.000	0.000	Yes

Table 6.13 reports consistency verification for the thirteen subcriteria. It is confirmed that decision makers' judgment is consistent enough to proceed.

#### 6.4.5.5 Alternatives

For this problem, the three alternative manufacturing processes considered for this problem are analyzed. On the hierarchical tree shown in Figure 6.4, these alternatives are located in the fourth level as Injection molding (ALT<sub>1</sub>), 3D printing (ALT<sub>2</sub>), and laser cutting (ALT<sub>3</sub>). Approaches of adapting data collected from manufactured brackets, experts' judgments are reported in Table 6.14, pairwise comparison judgments proposed by decision-makers as applied for each sub-subcriteria based on data from manufacturers, literature survey, and experience.

#### 1. Pairwise comparison

The judgments made by the decision-makers are based on each of the sub-subcriteria (SSC<sub>1</sub> to SSC<sub>38</sub>) mentioned towards the intended goal of sustainability performance.



Table 6.14 Decision makers' judgment on existing alternatives

SPI	ALT <sub>1</sub> / ALT <sub>2</sub>			ALT <sub>1</sub> / ALT <sub>3</sub>			ALT <sub>2</sub> / ALT <sub>3</sub>		
	Preference	Importance & Evaluation		Preference	Importance & Evaluation		Preference	Importance & Evaluation	
SSC <sub>1</sub>	ALT <sub>1</sub> /ALT <sub>2</sub>	Equal	1	ALT <sub>3</sub>	Strong	1/5	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>2</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>3</sub>	ALT <sub>2</sub>	Moderate	1/3	ALT <sub>1</sub>	Moderate	3	ALT <sub>2</sub>	Strong	5
SSC <sub>4</sub>	ALT <sub>2</sub>	Moderate	1/3	ALT <sub>1</sub>	Weak	2	ALT <sub>2</sub>	Moderate	3
SSC <sub>5</sub>	ALT <sub>1</sub> /ALT <sub>2</sub>	Equal	1	ALT <sub>1</sub>	Extreme	9	ALT <sub>2</sub>	Very strong	7
SSC <sub>6</sub>	ALT <sub>2</sub>	Moderate plus	1/4	ALT <sub>3</sub>	Moderate	1/3	ALT <sub>2</sub>	Weak	2
SSC <sub>7</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Strong	5	ALT <sub>3</sub>	Weak	1/2
SSC <sub>8</sub>	ALT <sub>2</sub>	Very strong	1/7	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong plus	6
SSC <sub>9</sub>	ALT <sub>2</sub>	Very strong	1/7	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong plus	6
SSC <sub>10</sub>	ALT <sub>2</sub>	Strong plus	1/6	ALT <sub>1</sub> /ALT <sub>3</sub>	Equally	1	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>11</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>12</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>13</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>14</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>15</sub>	ALT <sub>2</sub>	Very strong	1/7	ALT <sub>3</sub>	Moderate plus	1/4	ALT <sub>2</sub>	Moderate	3
SSC <sub>16</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>17</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>18</sub>	ALT <sub>2</sub>	Extreme	1/9	ALT <sub>3</sub>	Strong plus	1/6	ALT <sub>2</sub>	Moderate	3
SSC <sub>19</sub>	ALT <sub>2</sub>	Strong plus	1/6	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>20</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Weak	2	ALT <sub>3</sub>	Strong plus	1/6
SSC <sub>21</sub>	ALT <sub>2</sub>	Moderate plus	1/4	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>22</sub>	ALT <sub>2</sub>	Strong plus	1/6	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong plus	6
SSC <sub>23</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>24</sub>	ALT <sub>2</sub>	Strong	1/5	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Strong	5
SSC <sub>25</sub>	ALT <sub>1</sub>	Very, very strong	8	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Strong	1/5
SSC <sub>26</sub>	ALT <sub>1</sub>	Very strong	7	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>27</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>28</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>1</sub>	Weak	2	ALT <sub>3</sub>	Strong	1/5
SSC <sub>29</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>30</sub>	ALT <sub>1</sub>	Strong plus	6	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>31</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>32</sub>	ALT <sub>1</sub>	Moderate	3	ALT <sub>1</sub>	Strong plus	6	ALT <sub>2</sub>	Moderate	3
SSC <sub>33</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>1</sub>	Moderate	3	ALT <sub>3</sub>	Moderate	1/3
SSC <sub>34</sub>	ALT <sub>1</sub>	Strong	5	ALT <sub>3</sub>	Weak	1/2	ALT <sub>3</sub>	Strong	1/5
SSC <sub>35</sub>	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>2</sub>	Weak	2
SSC <sub>36</sub>	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>1</sub>	Weak	2	ALT <sub>3</sub>	Moderate plus	1/4
SSC <sub>37</sub>	ALT <sub>2</sub>	Moderate plus	1/4	ALT <sub>3</sub>	Weak	1/2	ALT <sub>2</sub>	Moderate plus	4
SSC <sub>38</sub>	ALT <sub>1</sub>	Moderate plus	4	ALT <sub>1</sub>	Strong plus	6	ALT <sub>2</sub>	Moderate	3

The selected important features reported in Table 6.5 can be used to explain the approach followed by decision-makers for these judgments as reported in Table 6.14, of alternatives for selected sub-subcriteria by considering three representative examples one from each sustainability dimension (material consumption from the environment, economic cost from economic and skill management from social dimensions) are considered. The judgment matrices

shown below are transformed from decision makers' judgment made on the three alternatives as reported in Table 6.14.

1. Material Consumption (SSC<sub>1</sub>)

SSC <sub>1</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1	1/5
ALT_2	1	1	1/3
ALT_3	5	3	1

2. Material efficiency (SSC<sub>2</sub>)

SSC <sub>2</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	6	3
ALT_2	1/6	1	1/4
ALT_3	1/3	4	1

3. Material availability (SSC<sub>3</sub>)

SSC <sub>3</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/3	3
ALT_2	3	1	5
ALT_3	1/3	1/5	1

4. Material value recovery (SSC<sub>4</sub>)

SSC <sub>4</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/3	2
ALT_2	3	1	3
ALT_3	1/2	1/3	1

5. Energy consumption (SSC<sub>5</sub>)

SSC <sub>5</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1	9
ALT_2	1	1	7
ALT_3	1/9	1/7	1

6. Renewables (SSC<sub>6</sub>)

SSC <sub>6</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/4	1/3
ALT_2	4	1	2
ALT_3	3	1/2	1

7. GHG emission (SSC<sub>7</sub>)

SSC <sub>7</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	7	5
ALT_2	1/7	1	1/2
ALT_3	1/5	2	1

8. Primary air pollutant (SSC<sub>8</sub>)

SSC <sub>8</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/7	1/2
ALT_2	7	1	6

ALT_3	2	1/6	1
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9. Secondary air pollutant (SSC<sub>9</sub>)

SSC <sub>9</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/7	1/2
ALT_2	7	1	6
ALT_3	2	1/6	1

10. Waste (SSC<sub>10</sub>)

SSC <sub>10</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/6	1
ALT_2	6	1	4
ALT_3	1	1/4	1

11. Fines (SSC<sub>11</sub>)

SSC <sub>11</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	6	3
ALT_2	1/6	1	1/4
ALT_3	1/3	4	1

12. Sanctions (SSC<sub>12</sub>)

SSC <sub>12</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	7	3
ALT_2	1/7	1	1/4
ALT_3	1/3	4	1

13. Expenditure (SSC<sub>13</sub>)

SSC <sub>13</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	8	3
ALT_2	1/8	1	1/5
ALT_3	1/3	5	1

14. Impact (SSC<sub>14</sub>)

SSC <sub>14</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	7	4
ALT_2	1/7	1	1/3
ALT_3	1/4	3	1

15. Strategy (SSC<sub>15</sub>)

SSC <sub>15</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/7	1/4
ALT_2	7	1	3
ALT_3	4	1/3	1

16. Value (SSC<sub>16</sub>)

SSC <sub>16</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	8	3
ALT_2	1/8	1	1/5
ALT_3	1/3	5	1

17. Cost (SSC<sub>17</sub>)

SSC <sub>17</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	8	3
ALT_2	1/8	1	1/5
ALT_3	1/3	5	1

18. Innovation (SSC<sub>18</sub>)

SSC <sub>18</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/9	1/6
ALT_2	9	1	3
ALT_3	6	1/3	1

19. Benefit plan (SSC<sub>19</sub>)

SSC <sub>19</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/6	1/2
ALT_2	6	1	4
ALT_3	2	1/4	1

20. Wages (SSC<sub>20</sub>)

SSC <sub>20</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	6	2
ALT_2	1/6	1	1/6
ALT_3	1/2	6	1

21. Suppliers (SSC<sub>21</sub>)

SSC <sub>21</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/4	1/2
ALT_2	4	1	4
ALT_3	2	1/4	1

22. Local community (SSC<sub>22</sub>)

SSC <sub>22</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/6	1/2
ALT_2	6	1	6
ALT_3	2	1/6	1

23. Investment (SSC<sub>23</sub>)

SSC <sub>23</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	8	4
ALT_2	1/8	1	1/3
ALT_3	1/4	3	1

24. Impact knowhow (SSC<sub>24</sub>)

SSC <sub>24</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/5	1/2
ALT_2	5	1	5
ALT_3	2	1/5	1

25. Employment type (SSC<sub>25</sub>)

SSC <sub>25</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	8	3
ALT_2	1/8	1	1/5
ALT_3	1/3	5	1

26. Job creation (SSC<sub>26</sub>)

SSC <sub>26</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	7	4
ALT_2	1/7	1	1/3
ALT_3	1/4	3	1

27. Job security (SSC<sub>27</sub>)

SSC <sub>27</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	6	4
ALT_2	1/6	1	1/3
ALT_3	1/4	3	1

28. Performance (SSC<sub>28</sub>)

SSC <sub>28</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	5	2
ALT_2	1/5	1	1/5
ALT_3	1/2	5	1

29. Injury rate (SSC<sub>29</sub>)

SSC <sub>29</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	6	4
ALT_2	1/6	1	1/3
ALT_3	1/4	3	1

30. Education (SSC<sub>30</sub>)

SSC <sub>30</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	6	4
ALT_2	1/6	1	1/3
ALT_3	1/4	3	1

31. Training (SSC<sub>31</sub>)

SSC <sub>31</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	5	3
ALT_2	1/5	1	1/3
ALT_3	1/3	3	1

32. Skill management (SSC<sub>32</sub>)

SSC <sub>32</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	3	6
ALT_2	1/3	1	3
ALT_3	1/6	1/3	1

33. Career development (SSC<sub>33</sub>)

SSC <sub>33</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	5	3
ALT_2	1/5	1	1/3
ALT_3	1/3	3	1

34. Customer satisfaction (SSC<sub>34</sub>)

SSC <sub>34</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	5	1/2
ALT_2	1/5	1	1/5
ALT_3	2	5	1

35. Conformity (SSC<sub>35</sub>)

SSC <sub>35</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	4	4
ALT_2	1/4	1	2
ALT_3	1/4	1/2	1

36. Values (SSC<sub>36</sub>)

SSC <sub>36</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	4	2
ALT_2	1/4	1	1/4
ALT_3	1/2	4	1

37. Equity and fairness (SSC<sub>37</sub>)

SSC <sub>37</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	1/4	1/2
ALT_2	4	1	4
ALT_3	2	1/4	1

38. Efficiency (SSC<sub>38</sub>)

SSC <sub>38</sub>	ALT_1	ALT_2	ALT_3
ALT_1	1	4	6
ALT_2	1/4	1	3
ALT_3	1/6	1/3	1

Once the judgment matrices are generated, the next step of determining the priority vector for these three alternatives is done for each of the thirty-eight sub-subcriteria.

## 2. Priority vector

The priority vector is determined first by performing sums of each column of judgment matrices and by then by dividing each element of the matrix by the column total and calculating the average of the elements of each row of the matrix (priority vector) for sub-subcriteria. The result is reported in Table 6.15 which is then used to determine values of maximum eigenvalue relevant to check consistency verification.

Table 6.15 Priority vectors for alternatives

1. Material Consumption (SSC<sub>1</sub>)

SSC <sub>1</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.143	0.200	0.130	0.158
ALT_2	0.143	0.200	0.217	0.187
ALT_3	0.714	0.600	0.652	0.655

2. Material efficiency (SSC<sub>2</sub>)

SSC <sub>2</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.667	0.545	0.706	0.639
ALT_2	0.111	0.091	0.059	0.087
ALT_3	0.222	0.364	0.235	0.274

3. Material availability (SSC<sub>3</sub>)

SSC <sub>3</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.231	0.217	0.333	0.260
ALT_2	0.692	0.652	0.556	0.633
ALT_3	0.077	0.130	0.111	0.106

4. Material value recovery (SSC<sub>4</sub>)

SSC <sub>4</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.222	0.200	0.333	0.252
ALT_2	0.667	0.600	0.500	0.589
ALT_3	0.111	0.200	0.167	0.159

5. Energy consumption (SSC<sub>5</sub>)

SSC <sub>5</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.474	0.467	0.529	0.490
ALT_2	0.474	0.467	0.412	0.451
ALT_3	0.053	0.067	0.059	0.059

6. Renewables (SSC<sub>6</sub>)

SSC <sub>6</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.125	0.143	0.100	0.123
ALT_2	0.500	0.571	0.600	0.557
ALT_3	0.375	0.286	0.300	0.320

7. GHG emission (SSC<sub>7</sub>)

SSC <sub>7</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.745	0.700	0.769	0.738
ALT_2	0.106	0.100	0.077	0.094
ALT_3	0.149	0.200	0.154	0.168

8. Primary air pollutant (SSC<sub>8</sub>)

SSC <sub>8</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.100	0.109	0.067	0.092
ALT_2	0.700	0.764	0.800	0.755
ALT_3	0.200	0.127	0.133	0.154

9. Secondary air pollutant (SSC<sub>9</sub>)

SSC <sub>9</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.100	0.109	0.067	0.092
ALT_2	0.700	0.764	0.800	0.755
ALT_3	0.200	0.127	0.133	0.154

10. Waste (SSC<sub>10</sub>)

SSC <sub>10</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.125	0.118	0.167	0.136
ALT_2	0.750	0.706	0.667	0.708
ALT_3	0.125	0.176	0.167	0.156

11. Fines (SSC<sub>11</sub>)

SSC <sub>11</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.667	0.545	0.706	0.639
ALT_2	0.111	0.091	0.059	0.087
ALT_3	0.222	0.364	0.235	0.274

12. Sanctions (SSC<sub>12</sub>)

SSC <sub>12</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.677	0.583	0.706	0.656
ALT_2	0.097	0.083	0.059	0.080
ALT_3	0.226	0.333	0.235	0.265

13. Expenditure (SSC<sub>13</sub>)

SSC <sub>13</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.686	0.571	0.714	0.657
ALT_2	0.086	0.071	0.048	0.068
ALT_3	0.229	0.357	0.238	0.275

14. Impact (SSC<sub>14</sub>)

SSC <sub>14</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.718	0.636	0.750	0.701
ALT_2	0.103	0.091	0.063	0.085
ALT_3	0.179	0.273	0.188	0.213

15. Strategy (SSC<sub>15</sub>)

SSC <sub>15</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.083	0.097	0.059	0.080
ALT_2	0.583	0.677	0.706	0.656
ALT_3	0.333	0.226	0.235	0.265

16. Value (SSC<sub>16</sub>)

SSC <sub>16</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.686	0.571	0.714	0.657
ALT_2	0.086	0.071	0.048	0.068
ALT_3	0.229	0.357	0.238	0.275



17. Cost (SSC<sub>17</sub>)

SSC <sub>17</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.686	0.571	0.714	0.657
ALT_2	0.086	0.071	0.048	0.068
ALT_3	0.229	0.357	0.238	0.275

18. Innovation (SSC<sub>18</sub>)

SSC <sub>18</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.063	0.077	0.040	0.060
ALT_2	0.563	0.692	0.720	0.658
ALT_3	0.375	0.231	0.240	0.282

19. Benefit plan (SSC<sub>19</sub>)

SSC <sub>19</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.111	0.118	0.091	0.107
ALT_2	0.667	0.706	0.727	0.700
ALT_3	0.222	0.176	0.182	0.194

20. Wages (SSC<sub>20</sub>)

SSC <sub>20</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.600	0.462	0.632	0.564
ALT_2	0.100	0.077	0.053	0.077
ALT_3	0.300	0.462	0.316	0.359

21. Suppliers (SSC<sub>21</sub>)

SSC <sub>21</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.143	0.167	0.091	0.133
ALT_2	0.571	0.667	0.727	0.655
ALT_3	0.286	0.167	0.182	0.211

22. Local community (SSC<sub>22</sub>)

SSC <sub>22</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.111	0.125	0.067	0.101
ALT_2	0.667	0.750	0.800	0.739
ALT_3	0.222	0.125	0.133	0.160

23. Investment (SSC<sub>23</sub>)

SSC <sub>23</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.727	0.667	0.750	0.715
ALT_2	0.091	0.083	0.063	0.079
ALT_3	0.182	0.250	0.188	0.206

24. Impact knowhow (SSC<sub>24</sub>)

SSC <sub>24</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.125	0.143	0.077	0.115
ALT_2	0.625	0.714	0.769	0.703
ALT_3	0.250	0.143	0.154	0.182

25. Employment type (SSC<sub>25</sub>)

SSC <sub>25</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.686	0.571	0.714	0.657
ALT_2	0.086	0.071	0.048	0.068
ALT_3	0.229	0.357	0.238	0.275

26. Job creation (SSC<sub>26</sub>)

SSC <sub>26</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.718	0.636	0.750	0.701
ALT_2	0.103	0.091	0.063	0.085
ALT_3	0.179	0.273	0.188	0.213

27. Job security (SSC<sub>27</sub>)

SSC <sub>27</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.706	0.600	0.750	0.685
ALT_2	0.118	0.100	0.063	0.093
ALT_3	0.176	0.300	0.188	0.221

28. Performance (SSC<sub>28</sub>)

SSC <sub>28</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.588	0.455	0.625	0.556
ALT_2	0.118	0.091	0.063	0.090
ALT_3	0.294	0.455	0.313	0.354

29. Injury rate (SSC<sub>29</sub>)

SSC <sub>29</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.706	0.600	0.750	0.685
ALT_2	0.118	0.100	0.063	0.093
ALT_3	0.176	0.300	0.188	0.221

30. Education (SSC<sub>30</sub>)

SSC <sub>30</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.706	0.600	0.750	0.685
ALT_2	0.118	0.100	0.063	0.093
ALT_3	0.176	0.300	0.188	0.221

31. Training (SSC<sub>31</sub>)

SSC <sub>31</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.652	0.556	0.692	0.633
ALT_2	0.130	0.111	0.077	0.106
ALT_3	0.217	0.333	0.231	0.260

32. Skill management (SSC<sub>32</sub>)

SSC <sub>32</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.667	0.692	0.600	0.653
ALT_2	0.222	0.231	0.300	0.251
ALT_3	0.111	0.077	0.100	0.096

33. Career development (SSC<sub>33</sub>)

SSC <sub>33</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.652	0.556	0.692	0.633
ALT_2	0.130	0.111	0.077	0.106
ALT_3	0.217	0.333	0.231	0.260

34. Customer satisfaction (SSC<sub>34</sub>)

SSC <sub>34</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.313	0.455	0.294	0.354
ALT_2	0.063	0.091	0.118	0.090
ALT_3	0.625	0.455	0.588	0.556

35. Conformity (SSC<sub>35</sub>)

SSC <sub>35</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.667	0.727	0.571	0.655
ALT_2	0.167	0.182	0.286	0.211
ALT_3	0.167	0.091	0.143	0.133

36. Values (SSC<sub>36</sub>)

SSC <sub>36</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.571	0.444	0.615	0.544
ALT_2	0.143	0.111	0.077	0.110
ALT_3	0.286	0.444	0.308	0.346

37. Equity and fairness (SSC<sub>37</sub>)

SSC <sub>37</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.143	0.167	0.091	0.133
ALT_2	0.571	0.667	0.727	0.655
ALT_3	0.286	0.167	0.182	0.211

38. Efficiency (SSC<sub>38</sub>)

SSC <sub>38</sub>	ALT_1	ALT_2	ALT_3	Priority vector
ALT_1	0.706	0.750	0.600	0.685
ALT_2	0.176	0.188	0.300	0.221
ALT_3	0.118	0.063	0.100	0.093

### 3. Consistency verification

In this analysis of consistency verification, for each of the sub-subcriteria, the size of the matrix (n) is 3 representing the three alternatives (ALT\_1, ALT\_2, and ALT\_3) and random index values (RI) is 0.52 obtained from Table 6.2. By using similar approaches as in sections 6.4.4.2 to 6.4.4.4, verification of the consistency of judgment is done and reported in Table 6.16.

Table 6.16 Consistency verification (Sub-subcriteria)

Alternative	$\lambda_{\max}$	Consistency Index (CI)	Consistency Ratio (CR)	Verification CR <10%
SSC <sub>1</sub>	3.043	0.022	0.042	Yes
SSC <sub>2</sub>	3.079	0.039	0.076	Yes
SSC <sub>3</sub>	3.055	0.028	0.053	Yes
SSC <sub>4</sub>	3.070	0.035	0.068	Yes
SSC <sub>5</sub>	3.009	0.005	0.009	Yes
SSC <sub>6</sub>	3.023	0.012	0.023	Yes
SSC <sub>7</sub>	3.025	0.012	0.024	Yes
SSC <sub>8</sub>	3.059	0.029	0.057	Yes
SSC <sub>9</sub>	3.059	0.029	0.057	Yes
SSC <sub>10</sub>	3.030	0.015	0.029	Yes
SSC <sub>11</sub>	3.079	0.039	0.076	Yes
SSC <sub>12</sub>	3.049	0.024	0.047	Yes
SSC <sub>13</sub>	3.067	0.034	0.065	Yes
SSC <sub>14</sub>	3.053	0.026	0.051	Yes
SSC <sub>15</sub>	3.049	0.024	0.047	Yes
SSC <sub>16</sub>	3.067	0.034	0.065	Yes
SSC <sub>17</sub>	3.067	0.034	0.065	Yes
SSC <sub>18</sub>	3.082	0.041	0.079	Yes
SSC <sub>19</sub>	3.015	0.007	0.014	Yes
SSC <sub>20</sub>	3.073	0.036	0.070	Yes
SSC <sub>21</sub>	3.080	0.040	0.077	Yes
SSC <sub>22</sub>	3.095	0.047	0.091	Yes
SSC <sub>23</sub>	3.031	0.015	0.029	Yes
SSC <sub>24</sub>	3.088	0.044	0.085	Yes
SSC <sub>25</sub>	3.067	0.034	0.065	Yes
SSC <sub>26</sub>	3.053	0.026	0.051	Yes
SSC <sub>27</sub>	3.085	0.043	0.082	Yes
SSC <sub>28</sub>	3.071	0.035	0.068	Yes
SSC <sub>29</sub>	3.085	0.043	0.082	Yes
SSC <sub>30</sub>	3.085	0.043	0.082	Yes
SSC <sub>31</sub>	3.055	0.028	0.053	Yes
SSC <sub>32</sub>	3.027	0.014	0.026	Yes
SSC <sub>33</sub>	3.055	0.028	0.053	Yes
SSC <sub>34</sub>	3.071	0.035	0.068	Yes
SSC <sub>35</sub>	3.080	0.040	0.077	Yes
SSC <sub>36</sub>	3.069	0.034	0.066	Yes
SSC <sub>37</sub>	3.080	0.040	0.077	Yes
SSC <sub>38</sub>	3.085	0.043	0.082	Yes

Table 6.16 reports consistency verification for the thirty-eight sub-subcriteria. It is confirmed that decision makers' judgment is consistent enough to proceed to a final aggregation of these alternatives into sub-subcriteria and subcriteria.

#### 6.4.5.6 Final aggregation

The final aggregation is done in three stages. The first step considered is an aggregation of the three criteria ( $C_1$ ,  $C_2$ , and  $C_3$ ) with the thirteen subcriteria ( $SC_1$  to  $SC_{13}$ ). Secondly, aggregation of subcriteria with the thirty-eight sub-subcriteria ( $SSC_1$  to  $SSC_{38}$ ) is done. The third and final stage of aggregation is done between each of the sub-subcriteria into the three alternatives

(ALT\_1, ALT\_2, and ALT\_3). The results of these aggregations are reported in Tables 6.17 to 6.19.

Table 6.17 Aggregation of subcriteria and criteria

Subcriteria		C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>
		0.25	0.5	0.25
SC <sub>1</sub>	0.391	0.098		
SC <sub>2</sub>	0.336	0.084		
SC <sub>3</sub>	0.039	0.010		
SC <sub>4</sub>	0.039	0.010		
SC <sub>5</sub>	0.196	0.049		
SC <sub>6</sub>	0.701		0.351	
SC <sub>7</sub>	0.085		0.043	
SC <sub>8</sub>	0.213		0.107	
SC <sub>9</sub>	0.341			0.085
SC <sub>10</sub>	0.364			0.091
SC <sub>11</sub>	0.167			0.042
SC <sub>12</sub>	0.077			0.019
SC <sub>13</sub>	0.051			0.013

Table 6.17 reports the aggregation of each criterion to subcriteria based on the priority vector values determined and reported in Tables 6.7 and 6.9. The aggregation results are obtained by multiplying each of these values.

Table 6.18 Aggregation of sub-subcriteria and subcriteria

Subcriteria		SC <sub>1</sub>	SC <sub>2</sub>	SC <sub>3</sub>	SC <sub>4</sub>	SC <sub>5</sub>	SC <sub>6</sub>	SC <sub>7</sub>	SC <sub>8</sub>	SC <sub>9</sub>	SC <sub>10</sub>	SC <sub>11</sub>	SC <sub>12</sub>	SC <sub>13</sub>
		0.098	0.084	0.010	0.010	0.049	0.351	0.043	0.107	0.085	0.091	0.042	0.019	0.013
SSC <sub>1</sub>	0.425	0.042												
SSC <sub>2</sub>	0.164	0.016												
SSC <sub>3</sub>	0.090	0.009												
SSC <sub>4</sub>	0.321	0.031												
SSC <sub>5</sub>	0.667		0.056											
SSC <sub>6</sub>	0.333		0.028											
SSC <sub>7</sub>	0.232			0.002										
SSC <sub>8</sub>	0.110			0.001										
SSC <sub>9</sub>	0.052			0.001										
SSC <sub>10</sub>	0.606			0.006										
SSC <sub>11</sub>	0.120				0.001									
SSC <sub>12</sub>	0.272				0.003									
SSC <sub>13</sub>	0.608				0.006									
SSC <sub>14</sub>	0.167					0.008								
SSC <sub>15</sub>	0.833					0.041								
SSC <sub>16</sub>	0.165						0.058							
SSC <sub>17</sub>	0.255						0.089							
SSC <sub>18</sub>	0.108						0.038							

SSC <sub>19</sub>	0.471	0.165	
SSC <sub>20</sub>	0.544	0.023	
SSC <sub>21</sub>	0.110	0.005	
SSC <sub>22</sub>	0.346	0.015	
SSC <sub>23</sub>	0.750	0.080	
SSC <sub>24</sub>	0.250	0.027	
SSC <sub>25</sub>	0.135	0.012	
SSC <sub>26</sub>	0.271	0.023	
SSC <sub>27</sub>	0.524	0.045	
SSC <sub>28</sub>	0.070	0.006	
SSC <sub>29</sub>	0.750	0.068	
SSC <sub>30</sub>	0.250	0.023	
SSC <sub>31</sub>	0.539	0.022	
SSC <sub>32</sub>	0.164	0.007	
SSC <sub>33</sub>	0.297	0.012	
SSC <sub>34</sub>	0.334	0.006	
SSC <sub>35</sub>	0.142	0.003	
SSC <sub>36</sub>	0.525	0.010	
SSC <sub>37</sub>	0.667	0.008	
SSC <sub>38</sub>	0.333	0.004	

Table 6.18 reports the aggregation of each subcriteria to sub-subcriteria based on the priority vector values determined and reported in Tables 6.12 and 6.15. The aggregation results are obtained by multiplying each of these values.

Table 6.19 Aggregation of alternatives and sub-subcriteria

Sub-subcriteria		ALT_1	ALT_2	ALT_3	AGG_1	AGG_2	AGG_3
SSC <sub>1</sub>	0.0415	0.158	0.187	0.655	0.007	0.008	0.027
SSC <sub>2</sub>	0.0160	0.639	0.087	0.274	0.010	0.001	0.004
SSC <sub>3</sub>	0.0088	0.260	0.633	0.106	0.002	0.006	0.001
SSC <sub>4</sub>	0.0313	0.252	0.589	0.159	0.008	0.018	0.005
SSC <sub>5</sub>	0.0559	0.490	0.451	0.059	0.027	0.025	0.003
SSC <sub>6</sub>	0.0280	0.123	0.557	0.320	0.003	0.016	0.009
SSC <sub>7</sub>	0.0023	0.738	0.094	0.168	0.002	0.000	0.000
SSC <sub>8</sub>	0.0011	0.092	0.755	0.154	0.000	0.001	0.000
SSC <sub>9</sub>	0.0005	0.092	0.755	0.154	0.000	0.000	0.000
SSC <sub>10</sub>	0.0059	0.136	0.708	0.156	0.001	0.004	0.001
SSC <sub>11</sub>	0.0012	0.639	0.087	0.274	0.001	0.000	0.000
SSC <sub>12</sub>	0.0027	0.656	0.080	0.265	0.002	0.000	0.001
SSC <sub>13</sub>	0.0059	0.657	0.068	0.275	0.004	0.000	0.002
SSC <sub>14</sub>	0.0082	0.701	0.085	0.213	0.006	0.001	0.002
SSC <sub>15</sub>	0.0408	0.080	0.656	0.265	0.003	0.027	0.011
SSC <sub>16</sub>	0.0580	0.657	0.068	0.275	0.038	0.004	0.016
SSC <sub>17</sub>	0.0894	0.657	0.068	0.275	0.059	0.006	0.025
SSC <sub>18</sub>	0.0380	0.060	0.658	0.282	0.002	0.025	0.011

SSC <sub>19</sub>	0.1654	0.107	0.700	0.194	0.018	0.116	0.032
SSC <sub>20</sub>	0.0232	0.564	0.077	0.359	0.013	0.002	0.008
SSC <sub>21</sub>	0.0047	0.133	0.655	0.211	0.001	0.003	0.001
SSC <sub>22</sub>	0.0148	0.101	0.739	0.160	0.001	0.011	0.002
SSC <sub>23</sub>	0.0800	0.715	0.079	0.206	0.057	0.006	0.017
SSC <sub>24</sub>	0.0267	0.115	0.703	0.182	0.003	0.019	0.005
SSC <sub>25</sub>	0.0115	0.657	0.068	0.275	0.008	0.001	0.003
SSC <sub>26</sub>	0.0231	0.701	0.085	0.213	0.016	0.002	0.005
SSC <sub>27</sub>	0.0447	0.685	0.093	0.221	0.031	0.004	0.010
SSC <sub>28</sub>	0.0060	0.556	0.090	0.354	0.003	0.001	0.002
SSC <sub>29</sub>	0.0682	0.685	0.093	0.221	0.047	0.006	0.015
SSC <sub>30</sub>	0.0227	0.685	0.093	0.221	0.016	0.002	0.005
SSC <sub>31</sub>	0.0225	0.633	0.106	0.260	0.014	0.002	0.006
SSC <sub>32</sub>	0.0068	0.653	0.251	0.096	0.004	0.002	0.001
SSC <sub>33</sub>	0.0124	0.633	0.106	0.260	0.008	0.001	0.003
SSC <sub>34</sub>	0.0065	0.354	0.090	0.556	0.002	0.001	0.004
SSC <sub>35</sub>	0.0027	0.655	0.211	0.133	0.002	0.001	0.000
SSC <sub>36</sub>	0.0101	0.544	0.110	0.346	0.006	0.001	0.004
SSC <sub>37</sub>	0.0085	0.133	0.655	0.211	0.001	0.006	0.002
SSC <sub>38</sub>	0.0042	0.685	0.221	0.093	0.003	0.001	0.000

Table 6.19 reports the aggregation of each sub-subcriteria to alternatives based on the priority vector values determined and reported in Tables 6.15 and 6.18. The aggregation results are obtained by multiplying each of these values.

Overall, Tables 6.17 to 6.19 report performance comparison values for each subcriteria and sub-subcriteria for the three dimensions of sustainability. Comparison tables are generated based on decision makers' judgments based on the proposed hierarchy. Performance value calculations for criteria and subcriteria, calculations of aggregations for criteria and sub-subcriteria, as well as final aggregation of the 38 sub-subcriteria with the three alternatives are done to evaluate overall sustainability performance. Results are reported in section 6.4.6 as the best alternatives of each criterion and finally as overall sustainability performance.

#### 6.4.6 Results and discussion

For this study, three alternatives, injection molding (ALT<sub>1</sub>), 3D printing (ALT<sub>2</sub>) and laser cutting (ALT<sub>3</sub>) have been evaluated for sustainability performance in the manufacturing of the Faceshield bracket. Sustainability evaluation is done based on the three dimensions, environment, economic and social, as criteria with corresponding subcriteria and sub-subcriteria. The first task was to identify criteria and subcriteria for each dimension of sustainability. Then based on the identified list of criteria, subcriteria, and alternatives, a decision tree is set up to breakdown the problem into different levels so that analysis on each comparison judgment matrix and calculation of aggregated criteria, subcriteria, sub-subcriteria, and alternatives is simplified.

The judgment table is setup after examining the evaluations of two experts. Through each judgment, a consistency verification is made by determining consistency ratios for each judgment matrix. The final aggregation results of the AHP analysis are reported in Figures 6.22 to 6.26.

#### 6.4.6.1. Best alternatives of the Environment criteria

Table 6.20 Results of environmental performance

Criteria	ENVIRONMENT														
Subcriteria	MATERIAL				ENERGY		EMISSION, EFFLUENT & WASTE				CONFORMANCE			TRANSPORT	
Sub-subcriteria	SSC <sub>1</sub>	SSC <sub>2</sub>	SSC <sub>3</sub>	SSC <sub>4</sub>	SSC <sub>5</sub>	SSC <sub>6</sub>	SSC <sub>7</sub>	SSC <sub>8</sub>	SSC <sub>9</sub>	SSC <sub>10</sub>	SSC <sub>11</sub>	SSC <sub>12</sub>	SSC <sub>13</sub>	SSC <sub>14</sub>	SSC <sub>15</sub>
ALTERNATIVES	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1
	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2
	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3
VALUES	0.007	0.010	0.002	0.008	0.027	0.003	0.002	0.000	0.000	0.001	0.007	0.002	0.004	0.006	0.003
	0.008	0.001	0.006	0.018	0.025	0.016	0.000	0.001	0.000	0.004	0.000	0.000	0.000	0.001	0.027
	0.027	0.004	0.001	0.005	0.003	0.009	0.000	0.000	0.000	0.001	0.000	0.001	0.002	0.002	0.011
RANKING	3	1	2	2	1	3	1	3	3	3	1	1	1	1	3
	2	3	1	1	2	1	3	1	1	1	3	3	3	3	1
	1	2	3	3	3	2	2	2	2	2	2	2	2	2	2

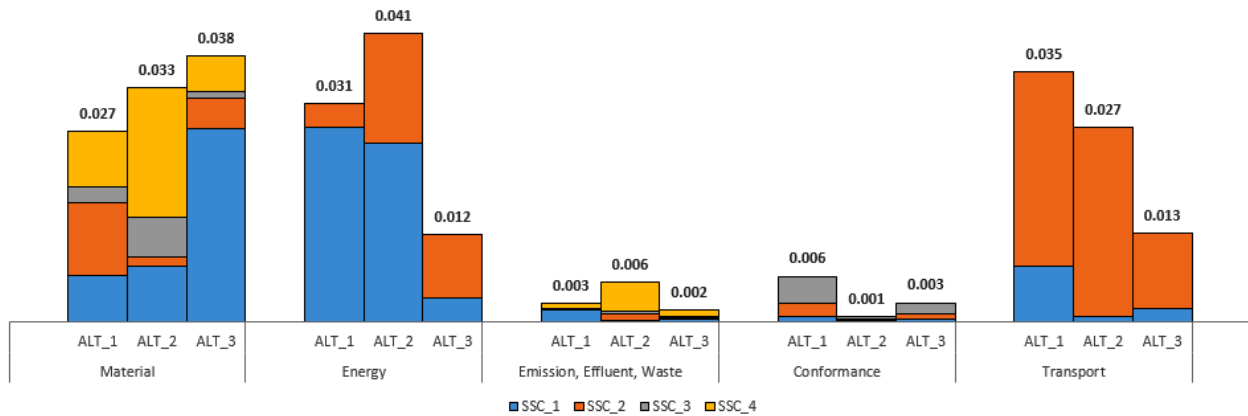


Figure 6.22 Environmental performance

	Material (SC <sub>1</sub> )	Energy (SC <sub>2</sub> )	Emission, effluent, waste (SC <sub>3</sub> )	Conformance (SC <sub>4</sub> )	Transport (SC <sub>5</sub> )
SSC_1	SSC <sub>1</sub>	SSC <sub>5</sub>	SSC <sub>7</sub>	SSC <sub>11</sub>	SSC <sub>14</sub>
SSC_2	SSC <sub>2</sub>	SSC <sub>6</sub>	SSC <sub>8</sub>	SSC <sub>12</sub>	SSC <sub>15</sub>
SSC_3	SSC <sub>3</sub>		SSC <sub>9</sub>	SSC <sub>13</sub>	
SSC_4	SSC <sub>4</sub>		SSC <sub>10</sub>		

Table 6.20 reports analysis results of the environmental performance of the three alternatives (ALT<sub>1</sub>, ALT<sub>2</sub> and ALT<sub>3</sub>) for the five subcriteria (material, energy, emission, effluent and waste, conformance, and transport), and the fifteen sub-subcriteria (SSC<sub>1</sub> – SSC<sub>15</sub>). Whereas Figure 6.22 represents environmental performance evaluation results based on the five subcriteria and the fifteen sub-subcriteria. The results show the following outcomes.

For material, the first score goes for laser cutting (0.038) shows better performance and the largest contribution came from SSC<sub>1</sub> (material consumption). Indeed, the use of thin plates and



the optimal arrangement of the parts on them greatly reduce material consumption. The second score is for 3D printing (0.033) and the major contributions came from material value recovery (SSC<sub>4</sub>) and finally, the third score goes to Injection molding (0.027) where the major contributor is material efficiency (SSC<sub>2</sub>).

For energy, 3D printing (0.041) ranked first where major contribution comes from energy consumption (SSC<sub>5</sub>), injection molding (0.031) ranked second where major contribution comes from SSC<sub>5</sub>, and laser cutting (0.012) ranked third where major contribution comes from SSC<sub>6</sub>. Energy is the most differentiating criterion, as the consumption of individual machines is low.

Emission, effluent, and waste, 3D printing (0.006) show better performance and the largest contributor is SSC<sub>10</sub> (Waste), injection molding shows second-best performance (0.003) where major contribution comes from SSC<sub>7</sub> (GHG emission) and third performance is recorded from laser cutting (0.018) where major contribution comes from SSC<sub>10</sub> (Waste).

Conformance, Injection molding (0.035) shows better performance where the largest contributor is SSC<sub>13</sub> (Expenditure), laser cutting (0.003) shows the second-best performance where the largest contributor is SSC<sub>13</sub> and 3D printing (0.001) shows the list performance where the largest contribution is SSC<sub>13</sub>.

Transportation, 3D printing (0.035) shows better performance and the largest contributor is SSC<sub>15</sub> (transportation strategy) and second-best performance from injection molding (0.027) and the third-best from laser cutting (0.013) where the major contributor is again SSC<sub>15</sub>. 3D printing allows local production that reduces transportation, unlike injection modeling.

#### 6.4.6.2. Best alternatives of the Economic criteria

Table 6.21 Results of economic performance

Criteria	ECONOMIC									
Subcriteria	ECONOMIC VIABILITY					MARKET PRESENCE			INDIRECT E IMPACT	
Sub-subcriteria	SSC <sub>16</sub>	SSC <sub>17</sub>	SC <sub>18</sub>	SSC <sub>19</sub>	SSC <sub>20</sub>	SSC <sub>21</sub>	SSC <sub>22</sub>	SSC <sub>23</sub>	SSC <sub>24</sub>	
ALTERNATIVES	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	
	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	
	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	
VALUES	0.038	0.059	0.002	0.018	0.013	0.001	0.001	0.057	0.003	
	0.004	0.006	0.025	0.116	0.002	0.003	0.011	0.006	0.019	
	0.016	0.025	0.011	0.032	0.008	0.001	0.002	0.017	0.005	
RANKING	1	1	3	3	1	3	3	1	3	
	3	3	1	1	3	1	1	3	1	
	2	2	2	2	2	2	2	2	2	

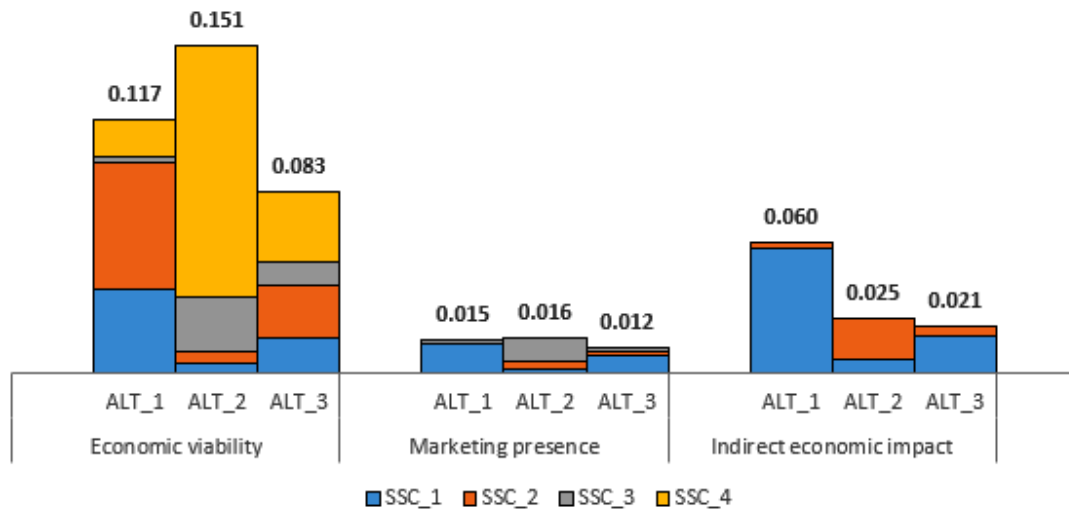


Figure 6.23 Economic performance

	Economic viability (SC <sub>6</sub> )	Marketing presence (SC <sub>7</sub> )	Indirect economic impact (SC <sub>8</sub> )
SSC_1	SSC <sub>16</sub>	SSC <sub>20</sub>	SSC <sub>23</sub>
SSC_2	SSC <sub>17</sub>	SSC <sub>21</sub>	SSC <sub>24</sub>
SSC_3	SSC <sub>18</sub>	SSC <sub>22</sub>	
SSC_4	SSC <sub>19</sub>		

Table 6.21 reports analysis results of the economic performance of the three alternatives (ALT<sub>1</sub>, ALT<sub>2</sub>, and ALT<sub>3</sub>) for the three subcriteria (economic viability, market presence, and indirect economic impact), and the nine sub-subcriteria (SSC<sub>16</sub> – SSC<sub>24</sub>). Whereas Figure 6.23 represents economic performance evaluation results based on the three subcriteria and the nine sub-subcriteria. The results show the following outcomes.

For economic viability, 3D printing (0.151) shows better performance and the largest contribution came from SSC<sub>19</sub> (benefit plan), Injection molding (0.117) shows the second-best performance where the largest contributor is SSC<sub>17</sub> (economic cost). And the third-best performance goes to laser cutting (0.083) where the largest contribution comes from SSC<sub>19</sub> (benefit plan). The economic viability is a cumulative performance measured based on judgments made for economic value, cost, innovation, and benefit plan as described in section 3.2.1, not just only the economic cost of machines.

For marketing presence, 3D printing (0.016) shows better performance and the largest contributor is related to SSC<sub>22</sub> (local community) whereas injection molding (0.015) where the largest contributor is related to SSC<sub>20</sub> (wages) and laser cutting (0.012) where the largest contribution comes from to SSC<sub>20</sub>, showed the second the third-best performance.

For indirect economic impact, injection molding (0.060) shows better performance and the largest contributor is SSC<sub>23</sub> (investment), 3D printing (0.025) is the second-best alternative where the

largest contribution comes from SSC<sub>24</sub> (impact knowhow) and laser cutting (0.021) is the third alternative where the largest contribution comes from SSC<sub>23</sub> (investment). The performance by ALT<sub>3</sub> is better due to the fact, that the judgments made on the investment are given higher intensity than ALT<sub>1</sub> and ALT<sub>2</sub>. Moreover, as mentioned in section 3.2.3, injection molding needs an industrial infrastructure of large machine tools, which could benefit the public through commercial, in-kind, pro-bono, or public good engagement.

#### 6.4.6.3. Best alternatives of the Social criteria

Table 6.22 Results of social performance

Criteria	SOCIAL													
Subcriteria	EMPLOYMENT				OHS		TRAINING & EDUCATION			PSS LABELING			GOVERNANCE	
Sub-subcriteria	SSC <sub>25</sub>	SSC <sub>26</sub>	SSC <sub>27</sub>	SSC <sub>28</sub>	SSC <sub>29</sub>	SSC <sub>30</sub>	SSC <sub>31</sub>	SSC <sub>32</sub>	SSC <sub>33</sub>	SSC <sub>34</sub>	SSC <sub>35</sub>	SSC <sub>36</sub>	SSC <sub>37</sub>	SSC <sub>38</sub>
ALTERNATIVES	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1	ALT1
	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2	ALT2
	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3	ALT3
VALUES	0.008	0.016	0.031	0.003	0.047	0.016	0.014	0.004	0.008	0.002	0.002	0.006	0.001	0.003
	0.001	0.002	0.004	0.001	0.006	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.006	0.001
	0.003	0.005	0.010	0.002	0.015	0.005	0.006	0.001	0.003	0.004	0.000	0.004	0.002	0.000
RANKING	1	1	1	1	1	1	1	1	1	2	1	1	3	1
	3	3	3	3	3	3	3	2	3	3	2	3	1	2
	2	2	2	2	2	2	2	3	2	1	3	2	2	3

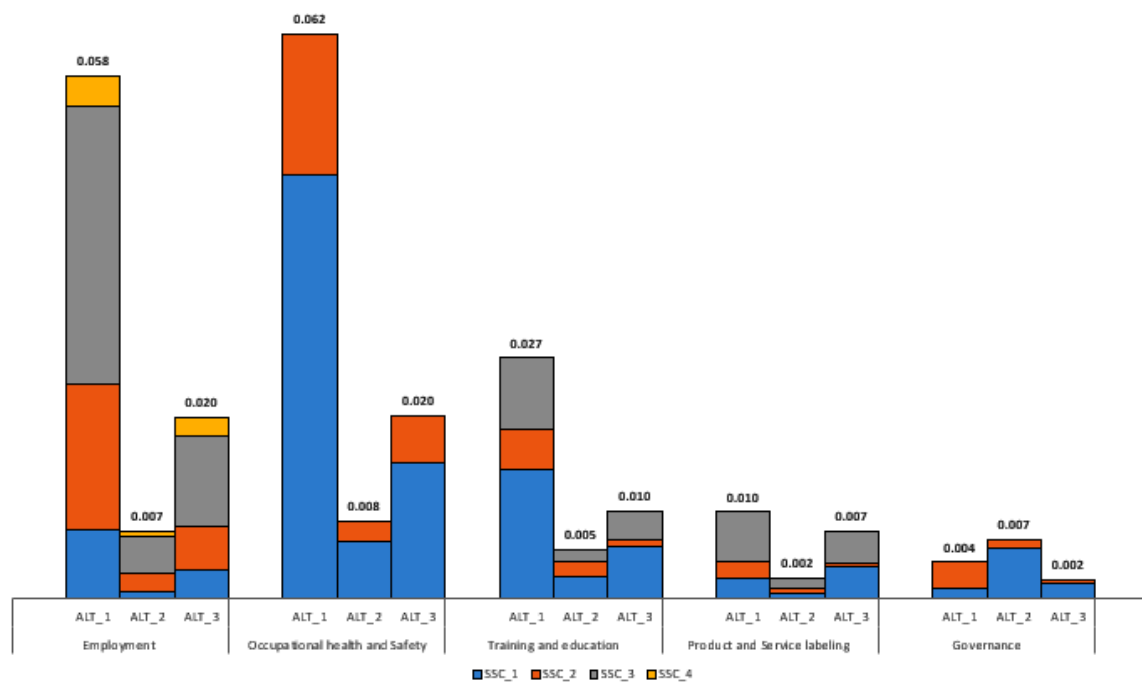


Figure 6.24 Social performance

	Employment (SC <sub>9</sub> )	OHS (SC <sub>10</sub> )	Training & education (SC <sub>11</sub> )	PSS labeling (SC <sub>12</sub> )	Governance (SC <sub>13</sub> )
SSC <sub>1</sub>	SSC <sub>25</sub>	SSC <sub>29</sub>	SSC <sub>31</sub>	SSC <sub>34</sub>	SSC <sub>37</sub>
SSC <sub>2</sub>	SSC <sub>26</sub>	SSC <sub>30</sub>	SSC <sub>32</sub>	SSC <sub>35</sub>	SSC <sub>38</sub>
SSC <sub>3</sub>	SSC <sub>27</sub>		SSC <sub>33</sub>	SSC <sub>36</sub>	
SSC <sub>4</sub>	SSC <sub>28</sub>				

Table 6.22 reports analysis results of social performance of the three alternatives (ALT<sub>1</sub>, ALT<sub>2</sub>, and ALT<sub>3</sub>) for the five subcriteria (employment, OHS, Training, and education, PSS labeling and governance), and the fourteen sub-subcriteria (SSC<sub>25</sub> – SSC<sub>38</sub>). Whereas, Figure 6.24 represents economic performance evaluation results based on the five subcriteria and the fourteen sub-subcriteria. The results show the following outcomes.

For employment, injection molding (0.058) shows a better performance where SSC<sub>27</sub> (Job security) is the largest contributor, laser cutting (0.020) is the second-best where the largest contributor is similarly SSC<sub>27</sub> and 3D printing (0.007) is the third alternative where the largest contributor is again SSC<sub>27</sub>. Indeed, injection modeling supposes the creation of a company in a conventional scheme, which tends to secure jobs.

For occupational health and safety, injection molding (0.062) shows better performance where SSC<sub>29</sub> (Injury rate) is the largest contributor, laser cutting (0.020) where the largest contribution is similarly SSC<sub>29</sub> and the third best is 3D printing (0.008) where the largest contribution is again SSC<sub>29</sub>.

For training and education, injection molding (0.027) shows better performance where SSC<sub>31</sub> (Training) is the largest contributor, laser cutting (0.010) is the second-best where the largest contribution is again SSC<sub>31</sub> and 3D printing (0.005) is the third-best alternative where the largest contribution equally contributed from SSC<sub>31</sub> (training) and SSC<sub>32</sub> (skill management).

For product and service labeling, injection molding (0.010) shows better performance where SSC<sub>36</sub> (values) is the largest contributor, laser cutting (0.007) is the second-best alternative where largest contributors are customer satisfaction (SSC<sub>34</sub>) and SSC<sub>36</sub> and 3D printing (0.002) is the third alternative with almost equal contribution came from SSC<sub>34</sub>, conformity (SSC<sub>35</sub>) and SSC<sub>36</sub>.

For governance, 3D printing (0.007) shows better performance where SSC<sub>37</sub> (Equity and Fairness) is the largest contributor, injection molding (0.004) where the largest contribution comes from efficiency (SSC<sub>38</sub>), and laser cutting (0.002) where the largest contribution comes from SSC<sub>37</sub>.

## 6.4.6.4 Overall sustainability

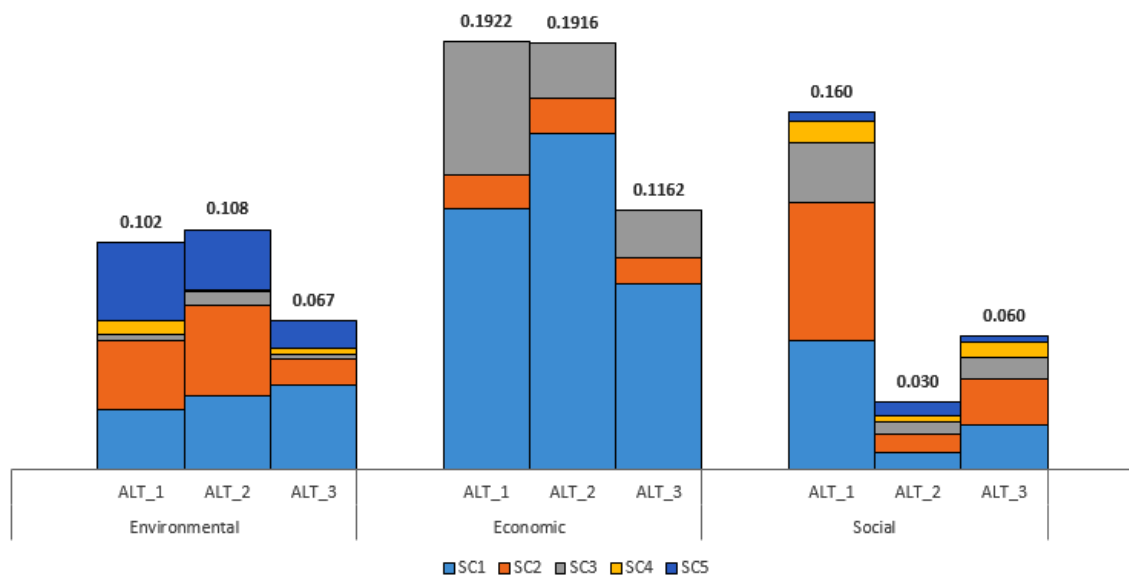


Figure 6.25 Overall sustainability performance for each sustainability dimension

	Environment	Economic	Social
	(C <sub>1</sub> )	(C <sub>2</sub> )	(C <sub>3</sub> )
SC1	SC <sub>1</sub>	SC <sub>6</sub>	SC <sub>9</sub>
SC2	SC <sub>2</sub>	SC <sub>7</sub>	SC <sub>10</sub>
SC3	SC <sub>3</sub>	SC <sub>8</sub>	SC <sub>11</sub>
SC4	SC <sub>4</sub>		SC <sub>12</sub>
SC5	SC <sub>5</sub>		SC <sub>13</sub>

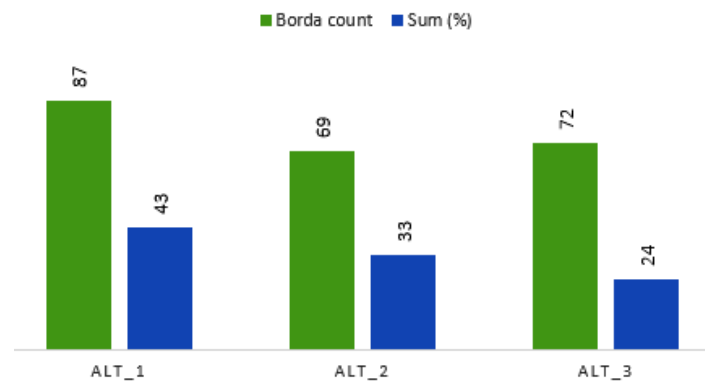


Figure 6.26 Overall sustainability for the three criteria [based on Borda count and Sum approach]

Figure 6.25 reports overall sustainability performance evaluation results based on the three dimensions. The results show that for environment, 3D printing (0.108 or 10.8%) > Injection molding (0.102 or 10.2%) > Laser cutting (0.067 or 6.7%). For economic, injection molding (0.1922 or 19.22%) > 3D printing (0.1916 or 19.16%) > laser cutting (0.1162 or 11.62%) and for social, injection molding (0.160 or 16%) > laser cutting (0.060 or 6%) > 3D printing (0.030 or 3%). These results reveal that for the environment dimension, 3D printing shows better

performance, and the largest contribution came from Energy ( $SC_2 = 0.041$  or 4.1%). The least contribution came from Conformance ( $SC_4 = 0.0007$  or 0.07%).

For economic dimension, injection molding (slightly larger) and 3D printing show almost equal better performance where the larger contributors are Economic viability ( $SC_1 = 0.117$  and  $SC_1 = 0.151$ ) respectively. The least contribution comes from Indirect economic impact ( $SC_3 = 0.060$  and  $SC_3 = 0.025$ ), respectively. Finally, for the social dimension, injection molding shows a better performance where OHS ( $SC_2 = 0.062$ ) is the largest contributor. The least contributor is Governance ( $SC_5 = 0.004$ ). Moreover, Figure 6.26 represents the overall sustainability performance of the three criteria based on the Borda count and sum approach. The ranking using Borda count is injection molding (first), laser cutting (second), 3D printing (third) and the ranking using sum approach is injection molding (first), 3D printing (second), and laser cutting (third).

## 6.5 Validation

The consistency verification performed for each judgment matrix is taken as a means of validation for each criterion, subcriteria, sub-subcriteria, and alternatives. A variation in decision makers' judgment for these or similar other processes could be accepted via proper check for consistency of judgment which could influence the final decision made.

## 6.6 Conclusions

In this study, a multicriteria decision-making method called Analytical Hierarchy Process is used to effectively evaluate the sustainability performance of three alternatives, injection molding, 3D printing, and Laser cutting used to manufacture three different Faceshield brackets. Based on the analysis, injection molding shows better overall sustainability performance. The total sum approach scores for injection molding, 3D printing, and laser cutting are 43, 33, and 24, and scores based on Borda count methodology are 87, 69, and 72 respectively.

Similarly, the contribution of each subcriteria and sub-subcriteria are calculated and the sustainability performance of each methodology is analyzed. Based on each dimension, for environment, 3D printing showed better performance (score = 0.108) where largest contribution came from energy (score = 0.041). For economic and social dimensions injection molding with scores of 0.192 (19.2%) and 0.160 (16%), respectively where largest contributions came from economic viability with a score of 0.117 (11.7%) and for the social dimension where occupational health and safety is the largest contribution with a score of 0.062 (6.2%).

To make final decisions, the Borda count method is introduced for comparison with the sum approach. For the sum approach, the scores of each of the 38 sub-subcriteria are added within each sustainability dimension. This results in scores of 0.428 for injection (ranked first), 0.329 for 3D printing (ranked second), and 0.242 for laser (ranked third). But since the frequency of

the rank of each alternative varies, the introduction of the Borda count method will assist a decision. Among the 38 sub-subcriteria, the frequency better preferences for injection molding, 3D printing, and laser cutting for the first choice were 23, 13, and 2, for the second choice 3, 5, and 30, and the third choice 12, 20 and 6 respectively. Thus, scores of Borda count are obtained by adding products of the frequency of the first choice by 3 and second choice by 2, and the third choice by 1. This method helps to avoid simple consideration of options that are preferred by the majority and allows considering better performances of other alternatives.

The importance of the findings that result from the analysis is helpful to evaluate the sustainability performance of similar products manufactured through different manufacturing methods, similar to the three methods utilized for this study. For this study, market assessment has not been done and some of the social dimensions might have a different performance which can be considered for future works. Future works on different components whether on PPE or related, should consider step by step gathering of full relevant information to assist decision makers' judgment so that the final decision reveals the real performance of utilized methodology to manufacture the desired part or product.

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## Chapter 7

### General Conclusion

This study primarily aimed to propose solutions for evaluating the sustainability performance of manufacturing products based on the gaps identified in understanding sustainability itself, subjective consideration of performance indicators, and poor sustainability performance evaluation methodology and related trends. Extant studies show that sustainability should be a concept beyond analyzing the environmental performance of manufacturing processes and systems and it must equally consider socio-economic performances because several manufacturing industries are currently being challenged by economic and financial priorities against environmental and social dimensions. The authors identified that gaps on the existing list of sustainability performance indicators which can be compared to standards for the selected application, analysis of sustainability performance of additive manufacturing processes, and proposing a multicriteria decision-making methodology that can compare and evaluate multiple, conflicting criteria to prioritize indicators based on the intended goal. Thus, this concluding chapter briefly reports this study's contributions to the body of knowledge, research implications, and future perspectives.

#### 7.1 Contribution to body of knowledge

Assuring sustainability greatly dependent on the type of manufacturing process. The shift towards design for additive manufacturing gave a unique opportunity for designers and manufacturers to significantly minimize or even avoid constraints associated with manufacturing. This is the primary advantage of additive manufacturing processes to give design flexibility with no additional cost. This is the most important but not the only benefit of additive manufacturing processes. Thus, the primary contribution of this study is sustainability performance analysis of AM through comparison with CM processes. It is found out that AM shows a better opportunity of sustainability performance when compared to conventional manufacturing processes.

Sustainability evaluation of AM is done by considering life cycle aspects of products which include pre-manufacturing (material selection and design), manufacturing, use, and post-use activities and logistics. Analysis results show that efficient utilization of resources, cost minimization with part complications, economic values of machinery needed for investment, assembly, tool handling, and shop floor automation, warehouse, training of employees, waste minimization, performance improvement of employees, end of life processing strategies, customer satisfaction, and public trust, transportation, location advantage, are major opportunities of AM when compared to CM processes.

The second contribution of this study is the development of a comprehensive list of sustainability performance indicators (SPIs) which can easily be compared to standards and is proposed based on a balanced consideration of the three dimensions in the design and manufacturing of engineering products. This has been done based on an extensive literature survey and assessment on topics such as level of subjectivity in understanding sustainability, life cycle considerations of products, quantification and interpretation strategy of each indicator, and trend of utilization for various applications and scopes.

This study proposed a total of 68 sustainability performance indicators which are categorized as second-level subcriteria and third-level sub-subcriteria (SPI). Accordingly, the study proposed 18 second-level categories of indicators, 8 for the environment, 3 for economic and 7 for social, and 68 for third-level subcategories where 29 are for the environment, 9 for economic, and 30 for social dimensions. For each subcategory detailed interpretation and whenever necessary a formulation on how to evaluate each indicator of the subcategory as well as the requirements of necessary data to determine each indicator is reported. Finally, validation for exhaustiveness of the proposed list of sustainable performance indicators by considering ten of the most widely used indicator sets and guidelines.

The validation process for exhaustiveness proved that there was a lack of equal consideration of the three dimensions of sustainability and less attention was given to the social dimension as compared to economic and environmental dimensions of sustainability. Through the outcome of this contribution, it is believed that the gap on the subjective understanding of sustainability itself based on scope or priority of manufacturers and unbalanced consideration of indicators from each dimension is better addressed and put a research direction for further improvement.

The third contribution of this study is the development of a new approach of sustainability performance evaluation of manufacturing an engineering product using multicriteria decision-making methodology of Analytic hierarchy. The methodology is proposed to formally describe, analyze, evaluate and optimize conflicting sustainability performance indicators (criteria) by selecting an application of Faceshield bracket manufacturing.

Industries and manufacturers tend to alleviate challenges of economic and financial priorities with environmental and social priorities for better sustainability once a comprehensive list of SPIs are identified. Consideration of an exhaustive list of sustainability performance indicators is often associated with conflicts between each indicator and to tackle this analysis is done by using multicriteria decision-making methodology. Therefore, as a third contribution, this study tried to perform sustainability performance evaluation of three manufacturing processes used to manufacture a Faceshield bracket, an application chosen, is done by using analytic hierarchy process. The methodology proposed is a comprehensive multicriteria decision-making methodology which is supposed to be a model for a similar investigation of sustainability

performance evaluation of design and manufacturing other engineering products. For the selected application, indicator selection has been done from the list of SPIs proposed as the first contribution by this study.

By considering an application, this study also analyzed how MCDM methodology can be applied for evaluating the sustainability of product manufacturing. This has been done by utilizing AHP for sustainable evaluation of three processes (injection molding, 3D printing, and laser cutting) used to manufacture three different types of Faceshield brackets. Based on the analysis, injection molding shows better overall sustainability performance. The total sum approach scores for injection molding, 3D printing, and laser cutting are 43, 33, and 24, and scores based on Borda count methodology are 87, 69, and 72, respectively. From the analysis, it was also possible to identify the contribution of each subcriteria and sub-subcriteria. Thus, results show that for the environment, 3D printing showed better performance (score = 0.108) where the largest contribution came from energy (score = 0.041) and for economic and social dimensions injection molding with scores of 0.192 (19.2%) and 0.160 (16%), respectively where largest contributions came from economic viability with a score of 0.117 (11.7%) and for the social dimension where occupational health and safety is the largest contribution with a score of 0.062 (6.2%).

The importance of the findings that result from the analysis is helpful to evaluate the sustainability performance of similar products manufactured through different manufacturing methods, similar to the three methods utilized for this study. For this study, market assessment has not been done and some of the social dimensions might have a different performance which can be considered for future works. Future works on different components whether on PPE or related, should consider step by step gathering of full relevant information to assist decision makers' judgment so that the final decision reveals the real performance of utilized methodology to manufacture the desired part or product.

## **7.2 Research implications**

It is widely understood that sustainable manufacturing is being taken as an effective solution to support the continuous growth and expansion of manufacturing engineering as a strategy for reducing the environmental impact and improving the socio-economic performance of the manufacturing industry. The findings of this study will be highly relevant and will certainly contribute to further policy input, practical applications, or subsequent research. These include;

- Create a common understanding about sustainability and pool of sustainability performance indicators to avoid incomplete and subjective consideration of performance indicators.
- Selection of manufacturing processes should be based on proper evaluation of performance towards sustainability.

- AM's potential of producing complex shapes, near net shaped fabrications, consolidated parts, multifunctional, lightweight, and associated opportunities of energy savings from transportation, assembly, and waste less manufacturing and so on are associated and relevant to sustainability performance and considering these opportunities will be highly beneficial for better sustainability.
- Further work must be done to avoid subjective understanding and unbalanced consideration of the three dimensions of sustainability regardless of scope and priority of industries or manufacturers.

### **7.3 Recommendations**

At the outset of this study, subjective understanding of sustainability and gaps in the overall evaluation are identified. To fully understand and measure the sustainability performance of manufacturing engineering products a balanced and comprehensive list of sustainability performance indicators and efficient utilization of multicriteria decision-making methodologies are highly needed. Thus, based on the major findings of this study, the following selected recommendations are proposed for better sustainability evaluation for manufacturing engineering products.

- Since the decision in the design and manufacturing of products depends on several conflicting objectives, understanding, defining, and implementing these conflicting objectives is highly recommended.
- For the selected case of Faceshield bracket manufacturing, selected and excluded list of SPIs are subjective to decision-makers, and excluded list of SPI vary and have a considerable effect on final evaluation for different applications. Thus, a careful indicator selection strategy is highly recommended.
- As applied in this study, structuring the problem in a hierarchy as well as making judgments on preference matrices are done by decision-makers and this must be carefully considered since it may have a wrong implication on final preferences unless done with knowledge. This can be further integrated into future studies with a focus on how problem structuring and experts' judgment could be best related to real problems.

## 7.4 Future perspectives

Based on the findings and recommendations, the following perspectives are relevant to take into account for future study.

Evolutions can be made both on the method and on the global approach to take into account durability in manufacturing. Concerning the method, three aspects can be enriched in the continuity of the work.

- The first concerns the updating and enrichment of all the SPIs. This point will be dealt with later.
- The second concerns the decision-making process. The study shows that a decision-making process based on so many criteria remains particularly complex and fragile. It is necessary to evolve the approach to improve its robustness. This finding also illustrates the fact that not everyone considers the same concept in the term sustainability. Depending on the point of view, expectations are different in terms of the environment, for example.
- The third point concerns the accuracy and relevance of the models associated with SPI. Indeed, the data available at the time of decision-making remains rather imprecise. The decision model must therefore be enriched to take this into account. Thus, improved decision-making methods could be made possible by appropriate data associated with each sustainability performance indicator. These data can be integrated into further studies on new materials and methodologies for a better assessment of durability through new analytical methods for process control and parameter optimization. Finally, efforts that many manufacturing industries have attempted to implement sustainable manufacturing should consider methods that are customized, non-reusable, and non-expandable.

As far as the overall approach is concerned, it appears that the key problem concerns the expression of all IPS. Establishing a relevant list is a complex problem because proposing an exhaustive list tends to increase its size. Moreover, this list depends very much on the company's assessment of the environmental and societal impact of the manufacturing process. This assessment necessarily evolves with time, according to technological developments. Thus several particular points can be assessed.

- The integration of manufacturing into the overall process of supplying products that meet the functional needs of customers implies that it will be necessary to take into account new SPI related to the interactions between the processes from the definition of the need to the delivery to the customer. The question is to move from sustainable manufacturing to sustainable customer satisfaction.



- This study isolated a set of 68 SPIs, given the current state of the literature. However, technological changes in manufacturing processes, products, and, above all, societal expectations may cause this set of SPIs to evolve. Indeed, we can see that the appreciation of sustainability is evolving in society. Environmental aspects have become more important. The same will be true for societal aspects. Therefore, the regular review of all IPS is a necessity.
- The consideration of sustainability in design and manufacturing processes interacts with the societal environment, through the consideration of standards for resource consumption, emissions, and human impact and guides for the development of new materials, processes, analytical methods, and products. In this way, SPIs are directly linked to changes in practices and standards. Similarly, integrating such SPI into manufacturing decision-making processes can also help to drive changes in practices and standards. Thus, the impact of manufacturing in the evolution of society is reinforced.
- This work makes it possible to express the sustainable performance of additive manufacturing in comparison with more conventional processes. Limitations are, therefore, identified. It may be relevant to use this method to identify the technological evolutions necessary to bring to additive manufacturing to make it more sustainable and thus become more competitive. Currently, additive manufacturing is looking for technological leaps enabling it to improve surface finishes, reduce post-treatment activities, improve production speed and volume, improve mechanical properties and reduce the impact of powder on human health. To do this, it is necessary to look for ways that necessarily take into account durability and above all improve it.

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## Appendix

### A. Data collection form for indicator selection (Faceshield bracket)

No.	SPI	By value or description			Supplementary description
		Injection molding (IM)	3D printing (3DP)	Laser cutting (LC)	
1	MAC	material weight <b>36gr/fs</b>	Weight = 38g material/fs The mass of the plastic and it is not considered for analysis = 32g = <b>32gr/fs</b>	72 fs per plate Time = 1.25 min /fs Weight = 13 gr / visor Weight of the batch of plates 25.92 kg for 25 plates. = <b>1.25 min/fs</b> <b>13gr/fs</b>	<ul style="list-style-type: none"> <li>Total material consumed to produce a single product</li> <li>Mass is determined from the weight of the piece since the total weight can be considered as an indicator for total material consumption.</li> <li>There is no support material used for all the processes.</li> <li>Based on comparison of material consumption, less embodied energy in material,</li> </ul>
2	MAE	Check Polypropylene recycling = check the amount of wasted material for 1 fs = <b>No</b>	Wasted material? = 18 fs / 750 gr 1 reel = 1000 gr 1 reel = 30 euros 750/18 - 38 = 4 gr = <b>4g</b>	Wasted material? = Surface A = 12506 mm <sup>2</sup> Plate A = 960,000 mm <sup>2</sup> PP density = 0.9 gr/cm <sup>3</sup>  Remains 59,508 mm <sup>2</sup> on the plate either 827 mm <sup>2</sup> per fs, or 993 mm <sup>3</sup> per fs, or 0.81 gr = <b>1.5g</b>	<ul style="list-style-type: none"> <li>Calculation of wasted material is done to determine material efficiency. This is done by comparing the weight of the final product obtained with the raw material purchased.</li> <li>Other alternatives include the wasted material and input material analysis.</li> <li>There is no recycling at the moment. The possibility of determining/planning for recycling will help existing waste to reenter the system to have better material efficiency. This means material efficiency can still be enhanced by introducing recycling.</li> <li>3DP – since the process doesn't involve removal of materials but rather making an object by layer upon layer building, the wasted material is minimized which in turn increases material efficiency.</li> </ul>
3	MAA	PP produced from the polymerization of propylene gas, using Ziegler-Natta catalyst. = Check material pellet manufacturing = Easy implementation Easy printing Faster Cheaper. Less withdrawal  = Polypropylene (0.8mm) =	PLA is made through the fermentation process from renewable resources such as corn starch, sugarcane, tapioca root. = Alternatives of ABS, PETG, TPU95 Ease of implementation Easy printing Faster Cheaper. Less withdrawal after cooling = Recycling is possible and replacement of virgin PLA over	wide range of material = the maximum thickness of 6mm for PP = The dissolution or precipitation technic is used for PP recycling (Poulakis and Papaspyrides, 1997) and confirmed that properties remained intact after recovery. = Check how PP is manufactured and PP plate is made? = Ease of implementation and cost =	<ul style="list-style-type: none"> <li>Alternatives among PETG, ABS, ASA, Nylon, etc. but thermoplastics like PVA, PC, HDPE are not widely used in commercially available devices (Davis et al., 2019).</li> <li>The material availability, portfolio, or range of materials is comparable between processes.</li> <li>Exhaustive alternatives need further analysis. Based on available alternatives, weight can be given for the three methods for the criteria, 'MAA'. This is done by exhaustive assessment of material portfolio for the intended part for the three processes.</li> <li>For IM, the criteria for selecting a material is not mentioned and it needs further assessment.</li> <li>For IM, materials including Polycarbonate (PC), ABS, Polypropylene (PP), Polybutylene terephthalate (PBT) [1]</li> </ul>

		What are existing availability options? = <b>PP</b> (easy)	recycled is possible (Maga et al., 2019). = <b>PLA</b> (larger MAA)	PP, PMMA, Teflon, wood, foam = <b>PP</b> (plate, difficult)	<ul style="list-style-type: none"> <li>For <b>3DP</b>, the criteria for selecting the material are ease of implementation, fast printing, cheaper and less waste. PLA (Polylactic acid) is used but other alternatives such as ABS, PETG, and TPU95 can be used.</li> <li>For <b>LC</b>, the criteria for selecting the material include ease of implementation and cost.</li> <li><u>Material for the 3DP process</u>: to compare the embedded energy in the raw material used, it is necessary to assess how the coil is made, PLA.</li> <li><u>Material for LC</u>: to compare the embedded energy consumption in materials used, it is necessary to assess how the PP and the plate are made for LC. Other options are PMMA, Teflon, wood, and foam.</li> <li>The embedded energy in materials preparations is not included as relevant information is not available.</li> </ul>
4	MAR	Yes	Yes PLA can be recycled (melt and reshaped) easily without degrading its mechanical property.	Yes	<ul style="list-style-type: none"> <li>More on recycling of materials for all processes.</li> <li>PLA recycling is under development (Maga et al., 2019)</li> </ul>
5	MAV	= <b>Yes</b>	PLA can be recycled (melt and reshaped) easily without degrading its mechanical property. = PLA is bio-based polymers produced commercially and recycling is possible and compostable. Th = <b>Yes</b>	= <b>Yes</b>	<ul style="list-style-type: none"> <li>Recycling of each material for the three processes should be checked by taking used materials as reference.</li> <li>Possible end of life value recovery options such as reuse, refurbishing,</li> <li>PLA is a commercial product and recycling as well as composting is possible in industrial facilities (Maga et al., 2019). PLA is mainly used for short-lived products like Packaging.</li> <li>Recycling of PP is comprised of dissolution of the plastic in an appropriate solvent (Poulakis and Papaspyrides, 1997)</li> </ul>
6	RMA	Use of renewable materials = No	Use of renewable materials = No	Use of renewable materials = No	<ul style="list-style-type: none"> <li>This product didn't use renewable materials.</li> <li>But utilization of renewable materials will be based on the utilization of cleaner energy, low energy content, recyclable or reusable materials.</li> <li>Discovering the embedded energy in the production of raw materials will give some hint on this part.</li> </ul>
7	ENC	Energy consumption = n/a = 500 Wh	Energy consumption = A 150W machine run for 2:30h (for a single fs) 150*2.5 = 375 Wh	lots of energy consumption for cooling = Laser tube = 150W Total power = 2.5KW = 52 Wh	<ul style="list-style-type: none"> <li><b>3DP</b>: To produce one bracket, takes 2h30 with a 150W machine or 375Wh. Does this mean a single bracket takes 2h30 to fully manufacture?</li> <li><b>LC</b>: Tube laser 150 W, Total puissance 2,5 kW, 52 Wh</li> <li>Direct and indirect energy consumption. Energy demand in fuel, electricity, for transportation.</li> <li>The energy consumption in extraction, refinement, and transportation of material (if not included in 'MAC' section).</li> </ul>

					<ul style="list-style-type: none"> <li>Indirect energy consumption by lighting, HVAC, etc.</li> </ul>
8	ENE	Means of minimizing waste = No	Means of minimizing waste = No	Means of minimizing waste = No	<ul style="list-style-type: none"> <li>It is a strategy to improve energy efficiency. This can be mainly implemented at the process level than in the product.</li> <li>Is the embedded energy in raw material considered?</li> <li>It is a strategy</li> </ul>
9	ENR	It is difficult to propose an energy efficient on the process level (on PP, on the machine) = <b>Less</b>	Utilization of recycled PLA rather than producing virgin PLA and processing = <b>Larger</b>	Use heat as a laser to cut, = <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data</li> <li>Initiative for energy-efficient products and processes to minimize direct and indirect energy requirements.</li> <li>The utilization of clean energy systems tends to minimize GHG emissions.</li> </ul>
10	GHG		Carbon neutral and doesn't emit toxic fumes = GHG emission occurs during extrusion but more importantly through raw material treatment, transportation and compression. = <b>Larger</b>		<ul style="list-style-type: none"> <li>No primary data</li> <li>Generation of CO<sub>2</sub> and CH<sub>4</sub> rates</li> <li>Corresponding GWP values for overall energy consumption for PLC.</li> <li>In the year 2013, the manufacturing sector contributed 19% of the GHG emission in the economic activity of EU countries (Saad et al., 2019). Checked in 2019 for possible contributions from CM and AM processes.</li> <li>This also considers strategies to minimize emissions through minimized energy/resource consumption.</li> <li>Detailed info could help determine the values such as GHG emissions by process and product level.</li> <li>For PLA, the amount of carbon converted into methane is less than 0.1% and leads neither to significant GHG nor to savings of energy (Maga et al., 2019).</li> <li></li> <li>A study by (Maga et al., 2019) on the recycling effect of PLA in different scenarios of mechanical, chemical, solvent-based, and thermal recycling and found out that the GHG contribution during treatment, transportation, and contribution of PLA is more than the contribution due to extrusion. For example, for chemical recycling, 18% whereas raw material treatment, transportation, and compression contribute 9%, 6%, and 4% respectively.</li> <li>Recycling as compared to thermal processing of PLA show higher GHG saving. For example, GWI reduction from 30% to 120%.</li> </ul>
11	PAP	Emissions during heating of injection cylinders and molds. = No decomposition products but air emissions occur during processing (check quantity.)	PLA 4 to 5µg/min = <b>Lesser</b>	emission from part trimming = What about PP? = <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data</li> <li>Direct emissions such as CO<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub>, CO, PM<sub>10</sub>, VOC, particulates, etc.</li> <li>Especially when using PLA for 3DP, it is necessary to check the melting temperature, if greater than 200°C, emissions may be harmful to human health (Bravi et al., 2019).</li> </ul>



		= What about for PP? = ABS 10 to 110µg/min = <b>Large</b>			<ul style="list-style-type: none"> <li>Check the thresholds defined by the French or other international decrees for VOCs regulation.</li> <li>The VOCs emitted ABS and HIPS range from 10 to 110µg/min and PLA from 4 to 5 µg/min (Azimi et al., 2016).</li> <li>Highest processing and decomposition temperatures of PP (275°C) and 300°C respectively (Pun et al., 2003). But decomposition products are not formed at or near injection molding temperatures. In IM, volatile emissions are from the vents in heating/injection cylinders and molds.</li> </ul>
12	SAP	The IM process generates environmental emissions due to high temp melting. = <b>Large</b>	VOCs emissions during operation of 3DP, extrusion, = <b>low (operation)</b>	= With poor ventilation, fumes from laser cutting of plastics may affect the operator = for PP, melt temperature ranges between 200 and 318°C = <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data</li> <li>Smog (if coal burning), SO<sub>2</sub>, Ozone, and other pollutants from NOX and VOCs.</li> <li>According to (Davis et al., 2019), numerous VOCs and particles are released into the indoor air, with 216 individual VOCs identified. The selection of filament material will indicate the VOCs that would lead to an impact on human health. The utilization of low-emitting 3D printers and filaments would minimize VOC emissions.</li> </ul>
13	SPI	No	No	No	<ul style="list-style-type: none"> <li>No smoke</li> <li>Is there any spill, liquid waste, etc.?</li> </ul>
14	WAS	Less waste resulted which can be melted and reused as compared to CNC during processing = transportation-related waste, Infrastructure location = <b>Large</b>	4gr/fs + coil + cardboard box Package without material = 500 gr = <b>4gr (?)</b> (recyclable, so not a problem but minimum waste costs less) = <b>Less</b>	Plate only Weight of waste per fs = 1.5 gr = <b>1.5gr (?)</b> = <b>Less</b>	<ul style="list-style-type: none"> <li>Besides the mass of the packages, are these recyclable or biodegradable materials, or how to minimize or avoid waste?</li> <li>The PLA waste can be sold on the market and will be used for profit generation (Maga et al., 2019). But the reduction of PLA waste is an advantage to minimize further processing and efficient utilization of materials.</li> </ul>
15	HAR	Emissions for heating PLA? = Yes	Emissions for heating PLA? Non (PLA is non-toxic) = Heating during manufacturing = Yes	Emissions for heating PLA? = Heating during manufacturing = Yes	<ul style="list-style-type: none"> <li>Heating during manufacturing for both processes</li> <li>How much heating? Can it be expressed in terms of heat consumption?</li> <li>Compare the toxicity of raw material processing and disposal.</li> <li>3DP and LC – require heating</li> </ul>
16	PSI	- = Less	Raw material PLA is produced from renewable energy and doesn't emit carbon and toxic fumes. - = High	- = Less	<ul style="list-style-type: none"> <li>No direct data</li> <li>It is an initiative to mitigate the environmental impact through energy saving, value-added services, and recycling strategies of the product.</li> </ul>
17	PSP	minimum packaging (needs explanation) = -	by increasing the size of the coils, the amount of packaging may be minimized =	Minimum possible = <b>possible</b>	<ul style="list-style-type: none"> <li>Packaging data is not quantified.</li> <li>IM – n/a</li> <li>3DP – recommended using increased coil size to minimize packaging.</li> <li>LC – n/a</li> </ul>

			<b>possible</b>		<ul style="list-style-type: none"> <li>The proposed solution of using increased coil size is based on an increased quantity of Faceshield production for 3DP and minimum packaging for LC. But it is important to give for a specific number of Faceshield production for both processes.</li> </ul>
18	EFI	- = Higher	PLA is made from renewable sources and less impact on the environment. Processing impact? = Less	- = Medium	<ul style="list-style-type: none"> <li>No direct data</li> <li>Noncompliance monetary fines for environmental during use and post-use.</li> <li>How can we make sure that products made using each process don't lead to monetary fines for possible non-conformance to environmental regulations?</li> </ul>
19	ESA	- = Large	- = Less	- = Medium	<ul style="list-style-type: none"> <li>No direct data</li> <li>No. of monetary sanctions for non-compliance with environmental sanctions.</li> <li>What about non-monetary sanctions?</li> </ul>
20	EEX	to minimize waste related to transport, expenditure is high = <b>High</b>	effect of raw material and process doesn't require expenditure for environmental protection = <b>less</b>	Check = <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data/remark to be made based on literature</li> <li>Environmental protection expenditure.</li> <li>It seems that utilization of processes that can't severely affect the process is valid for all processes. Therefore, this can be</li> </ul>
21	ITR	huge infrastructure for processing, associated transportation for material = <b>High</b>	No infrastructure can be located near the consumer, or near the material = <b>Less</b>	Check = <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data</li> <li>Environmental impact associated with transporting products, goods, materials,</li> <li>Existing data didn't provide comprehensive data on transport, the possibility of product manufacturing closer to consumers to minimize the impact of transportation (Khosravani and Reinicke, 2020).</li> </ul>
22	STR	Yes but expensive = <b>Less</b>	There is a high chance of establishing printing facilities near consumers/raw material sources = <b>Higher</b>	Yes, it can be done but the cost of establishing Fab Lab = <b>Medium</b>	<ul style="list-style-type: none"> <li>No primary data</li> <li>Strategy to introduce energy-efficient transport mode.</li> <li>This can be evaluated based on the possibility of manufacturing the bracket near customers or users where the impact of transportation can be minimized. For example, manufacture near consumers to avoid transportation energy or cost.</li> </ul>
23	ECE	Users can value a product's value by determining how thick/ thin one can make the visor using CM? = High/mass production Less for small scale = <b>High</b>	Users can value the product's value as using AM, it is possible to produce as thin as possible. = High for small scale Less for mass production = <b>Less</b>	used for mass production = High/mass production Less for small scale = <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data</li> <li>Economic value generated including revenue, operating cost, etc.</li> <li>The value of the product can be seen from different perspectives or the possibility of including relevant features such as variations on thickness, weight, etc., and the possibility of enhancing features related to compatibility in size and shape and mechanical property. Evaluation can be given in these aspects of weight, thickness, size, shape, and property.</li> </ul>
24	ECO	Costs such as machine, material, labor, etc. = Machine 20 € / h Plastic € 2.13 / kg Cadence 50 pcs / h 6h per day	Costs such as machine, material, labor, etc. = It is given that machine costs 3K€. Material costs 30€ per kg and the hourly rate	Costs such as machine, material, labor, etc. = Machine 15K€; hourly rate = 5€/h; material cost = 153€ for 25*72 visors or 0.085€/visor.	<ul style="list-style-type: none"> <li>More cost comparison schemes can also be introduced.</li> <li>The cost given is for machine, material, labor, manufacturing, repair, maintenance, and recycling.</li> <li><b>3DP</b> – According to cost structure by (Busachi et al., 2017), machine cost refers 74% of the total product cost. But this is</li> </ul>

		= Cost of a visor? = <b>More</b>	is 1 euro/hour. Cost of visor = 1.25€ for each visor and machine cost per visor = 2.5€. = 2.5€/visor = <b>Medium</b>	Thus, machine cost = 0.118€/visor. = 0.12 €/visor = <b>Less</b>	for big AM machines rather than desktop type 3DPs, check. Thus, overall economic performance depends on deposition rates and building capacities. The speed is low and is not convenient for mass production.
25	IRD	the inexpensive way for trial and error for innovation = Low	There is a high chance for R&D = <b>high</b>	? = Low	<ul style="list-style-type: none"> <li>Expenditures in R&amp;D.</li> <li>According to the data collected, there is a high chance of innovation opportunities using 3DP than it is in LC.</li> </ul>
26	FBA	NO	= Yes (why?)	= No	<ul style="list-style-type: none"> <li>There is a high opportunity of getting financial assistance from the government or other sources. But it is not clear why the FBA is 'No' for LC.</li> </ul>
27	WAG	High	Low	Medium	<ul style="list-style-type: none"> <li>No direct data</li> <li>Entry-level wages.</li> </ul>
28	SUP	Not easy = Less	Yes, WRT raw material PLA and very acceptable price for local use, cheap price and training cost = High	= Medium	<ul style="list-style-type: none"> <li>No direct data</li> <li>Policy or strategy for spending on locally based suppliers.</li> <li>PLA production using fermentation can engage many near local suppliers (for 3DP).</li> </ul>
29	LOC	High	Low	Medium	<ul style="list-style-type: none"> <li>No direct data</li> <li>Is there any possibility of special hiring requirements based on the process implemented?</li> </ul>
30	INV	Need an industrial infrastructure of large machine tool <b>Yes</b>	There is no need for infrastructure <b>No</b>	A structure like Fab Lab has to be developed <b>Yes</b>	<ul style="list-style-type: none"> <li>Infrastructure requirement and the impacts of investment. This could benefit the public through commercial, in-kind, pro-bono, or public good engagement.</li> </ul>
31	IMK	used in mass production, machine operation increased productivity = <b>More</b>	small scale but may create many jobs, encourage small business = <b>Less</b>	= <b>Medium</b>	<ul style="list-style-type: none"> <li>No direct data</li> <li>Possible economic impacts such as jobs created by suppliers, increase in productivity, and business-to-business activity.</li> <li></li> </ul>
32	EMT	Part design, mold design, machine operation, etc. = Larger	PLA is finding a growing market, opportunity but printer is being used by individuals = design and printing = Less	Part design, machine operation = Medium	<ul style="list-style-type: none"> <li>No direct data</li> <li>Evolution of total employee within time.</li> <li>This compares employment types based on the process selected to produce the product.</li> </ul>
33	EMJ	job creation WRT raw material Vs Processing = High / Medium	PLA, a high opportunity for job creation as the bioplastic industry is growing, job creation = High / Less	= High / Less	<ul style="list-style-type: none"> <li>No direct data</li> <li>Rate of new employee turnover. This can measure job creation and accessibility to the labor market.</li> <li>According to estimates of European Bioplastics, by 2030, 300,000 highly skilled jobs will be created in the European bio-market, more than 10 times its current numbers.</li> </ul>
34	EMR	-	-	-	<ul style="list-style-type: none"> <li>No direct data</li> </ul>

					<ul style="list-style-type: none"> <li>D</li> </ul>
35	EMS	Workplace safety? = Larger	Workplace safety? = Safety is not an issue at all since raw material as well as operation is not harmful (except the indoor operation of the printer) = No (Less)	With poor ventilation, fumes from laser cutting of plastics may affect the operator = Workplace safety? = Medium	<ul style="list-style-type: none"> <li>Exposure to harmful chemicals, adverse atmospheric conditions, length of working day hours, or overall workplace safety and comfort.</li> <li><b>3DP</b> – safety is not an issue at all. But safety concerns for LC are not mentioned. VOC emissions during extrusion operation in a confined place.</li> <li>PLA plastic is recognized <b>as safe</b> by the United States Food and Drug Administration. (But heating effects?)</li> </ul>
36	EMC	Complaint reports from employees. = No	Complaint reports from employees. = No	Fumes in the unventilated working area = No (maybe)	<ul style="list-style-type: none"> <li>Complaint reports from employees.</li> </ul>
37	EMP	Knowledge, skill, and competence needs = 3 days for the operator and 1 day for technician training. = <b>Large</b>	Knowledge, skill, and competence needs = Limited (no further detail) = <b>Limited</b>	Knowledge, skill, and competence needs = 30 mins for the operator and 2 days for technician training. = <b>Medium</b>	<ul style="list-style-type: none"> <li>Employment performance is based on key knowledge, skill, and competencies. What is needed?</li> <li>This depends on the complexity or ease of processing type.</li> <li>Software to develop the digital data.</li> </ul>
38	INR	Injury rate or work-related fatality = Frequency index = number of lost-time accidents x 1,000 / number of employees. Index = 45; 115,000 employees = Yes	Injury rate or work-related fatality = None	Injury rate or work-related fatality = None	<ul style="list-style-type: none"> <li>Lost time injury frequency rate (LTIFR) = [number of lost time in injuries in the reporting period]*1000000 (million) / [total hours worked in the reporting period]</li> <li>Example: LTIFR = 2.4 (means there were 2.4 lost time injuries for every one million man-hours worked).</li> <li>IM – Injury for every million man-hours worked (verify)</li> </ul>
39	EDU	education & training = Integrated into training = Yes	education & training = None	education & training = On the site	<ul style="list-style-type: none"> <li>Education and training on risk control to assist workforce members, families, and the community about OHS.</li> <li>This indicator has an indirect impact.</li> </ul>
40	RIS	No risk for people. Handling of pellets. Large economic volume = No	No risk for people. Handling light coils = No	No risk for people. Handling of 1.5 kg plates. 25 kg set. = No	<ul style="list-style-type: none"> <li>Utilization of nonhazardous input material or minimization of impact.</li> </ul>
41	TRE	= High	= Very low	= Low	<ul style="list-style-type: none"> <li>Training and education for skill enhancement to realize the product.</li> <li>Based on the process, the training hours are needed. This is the level of skill enhancement requirement to realize the product.</li> </ul>

42	SKM	Yes, in a usual educative process and in an industrial process = Large	No	Yes but the boost is low = Low	<ul style="list-style-type: none"> <li>Programs for skill management training and lifelong learning for continued employability and career.</li> <li>Skill management and lifelong learning</li> </ul>
43	CAD	High	None	Low	<ul style="list-style-type: none"> <li>This is the measure of providing regular performance and career development.</li> </ul>
44	PIN	Yes, material properties, security, process parameters = Yes	Yes, material properties, security, process parameters = Yes	Yes, material properties, security, process parameters = Yes	<ul style="list-style-type: none"> <li>Product information required by policy and procedures.</li> </ul>
45	NCR	= No labeling	= No labeling	= No Labeling	<ul style="list-style-type: none"> <li>No direct data</li> <li>Number of incidents for non-compliance to regulations and voluntary codes for PSS and labeling</li> </ul>
46	CUS	= <b>Yes</b>	= <b>Yes</b>	= <b>Yes</b>	<ul style="list-style-type: none"> <li>For the three processes, validation by the user, fatigue related to the weight or shape of the visor, it is very expensive to adapt.</li> <li>Selected customer satisfaction aspects such as safety, comfort, value at a reduced cost, etc. This can include the indicator of PUT (public trust).</li> <li>PLA is brittle behavior and mixing with environmentally friendly plastics will enhance this but this will also make recycling more difficult.</li> </ul>
47	PUT	Equal	Equal	Equal	<ul style="list-style-type: none"> <li>Public trust in the product through user-product relationship, the role of culture, user values, producer responsibility, regulation, etc.</li> </ul>
48	CON	Very complex adaptation, expensive (difficult) = <b>Less</b>	easy modification of the form = <b>High</b>	easy modification of the form = <b>Easy (medium)</b>	<ul style="list-style-type: none"> <li>x</li> <li>The level of quality or comfort expected by users depends on their need but based on the type of process measure of flexibility in adaptation work is very relevant to measure.</li> </ul>
49	VAL	= Lesser	= High	= Medium	<ul style="list-style-type: none"> <li>Means of respecting mandatory laws and regulations to PSS labeling to avoid fines.</li> </ul>
50	MAB	Equal	Equal	Equal	<ul style="list-style-type: none"> <li>Marketing benefits, laws, standards related to marketing communications.</li> </ul>
51	NCI	Equal	Equal	Equal	<ul style="list-style-type: none"> <li>Noncompliance incidents related to marketing benefits.</li> </ul>
52	SFI	Easy	More difficult	More difficult	<ul style="list-style-type: none"> <li>Social laws and regulations and associated fines can easily be identified through simple inspections such as compatibility, or health issues. Or comparison with health and safety regulation tests.</li> </ul>
53	SSA	Equal	Equal	Equal	<ul style="list-style-type: none"> <li>Non-monetary sanctions for non-compliance to social laws and regulations.</li> </ul>
54	TRP	-	-	-	<ul style="list-style-type: none"> <li>No direct data</li> <li>About boosting the level of transparency and connectivity with stakeholders.</li> </ul>
55	EQF	= <b>Less</b>	[Moral issue] there is a moral issue in the production of PLA. Spending on crops for bioplastics when many need it for food. But	= <b>Less</b>	<ul style="list-style-type: none"> <li>Equal rights and freedom</li> </ul>

			high freedom to own the printer = <b>High</b>		
56	EFF	Through training in the company = Medium	Self-training = High	Through company training and self- training. = Medium	<ul style="list-style-type: none"> <li>Method of enhancing efficiency or performance of an employee in a day and/or means of minimizing interruption factors.</li> </ul>

## B. Data collection form proposed for better decision makers' judgment

This data collection form is not directly utilized for this study but is put as a reference for better judgment and data collection.

Table B.1 Environment

SNo		Data type / name	Measure	Process
1.	MATERIAL	Materials consumed to produce each part	Kg	
2.		Material loaded into the system	Kg	
3.		Material wasted in all existing processes	Kg	
4.		Percentage of material recycled	%	
5.		Percentage of material recycled?	%	
6.	ENERGY	Number of facilities needed for part production	number	
7.		Type of power source utilized	type	
8.		The power demand of respective facilities	KW	
9.		Operational efficiency of facilities	%	
10.		Operational time of facilities	hours	
11.	WATER	Energy saved/minimized due to new process or system	KW	
12.		Water consumed or <b>#13 and #14</b>	L or m <sup>3</sup>	
13.		Water flow rate	[m <sup>3</sup> /s]	
14.		Water flow time	[m <sup>3</sup> /s]	
15.		Water withdrawal throughout the process	m <sup>3</sup>	
16.	EMISSION, EFFLUENT, WASTE	Water recycled or reused	%	
17.		GHG emission or <b>#18 to #20</b>	[Kg CO2 eq.]	
18.		Total energy consumption	KW	
19.		Generation rates (r) of CO2, CH4, NO2		
20.		Global warming potentials (GWP) of CO2, CH4, NO2.		
21.		Amount of GHG reduction or <b># 22 to #28</b>		
22.		The emission factor of GHG from a local grid power supply		
23.		Life cycle emission of clean energy		
24.		The total installed capacity of clean energy		
25.		The operational lifetime of a clean power system	hours	
26.		Overnight cost of clean power system		
27.		Variable O&M cost of clean power system		
28.		Fixed O&M cost of clean power system		
29.		Life cycle emission of a product or <b>#30 to #33</b>		
30.		GHG emission of material		
31.		GHG emission during the use stage		
32.		GHG emission during the end of life stage or <b>#33 to #37</b>		
33.		GHG emission of material i		
34.		Reuse rate of material i		
35.		Recycle rate of material i		
36.		The recovery rate of material i		
37.		Recovered heat capacity of material i		
38.		Pollutant emission or <b>#39 to #41</b>		
39.		Onsite energy consumption	KW	
40.		NOx generation rate		
41.		SOx generation rate		
42.		Amount of hazardous waste or <b>#43 to #46</b>		

43.	CONFORMANCE	The volume of hazardous waste	m <sup>3</sup>	
44.		The density of the hazardous waste	Kg/m <sup>3</sup>	
45.		Process time	hours	
46.		The time between tank refills	hours	
47.		Amount of waste to landfill or <b>#48 and #49</b>	Kg	
48.		The fraction of waste to landfill	%	
49.		Mass of material removed	Kg	
50.		Amount of waste to recycling or <b>#49 and #51</b>	Kg	
51.		The fraction of waste to recycling	%	
52.		GHG emission converted from cost or <b>#53 and #55</b>		
53.	TRANSPORT	Life cycle cost of the product	\$	
54.		GHG emission coefficient of electricity		
55.		The unit cost of energy		
56.		The number of monetary sanctions for non-compliance to environmental regulations.		
57.		Environmental impact of transporting products		
58.		Transportation or logistics strategies implemented		

Table B.2 Economic dimension

SNo	Data type / name		Measure	Process
1.	ECONOMIC VALUE	Economic value	\$	
2.		The total cost incurred on the product or <b>#3 to #5</b>	\$	
3.		The total cost of material	\$	
4.		Total cost during use	\$	
5.		Total cost after end of life	\$	
6.		The cost associated with the operation or <b>#7 to #10</b>	\$	
7.		Cost of consumables	\$	
8.		Cost of electrical energy	\$	
9.		Process time		
10.		Labor cost	\$	
11.		The total cost of the product or <b>#12, #17, 21, and #27</b>	\$	
12.		Material cost or <b>#13 to #16</b>	\$	
13.		Material cost on a mass basis	\$	
14.		Material density		
15.		Part volume		
16.		The fraction of material scrapped during manufacturing		
17.		Tooling cost or <b>#18 to #20</b>	\$	
18.		Cost of dedicated tooling	\$	
19.		Number of complete toolsets needed for the production run		
20.		Number of identical parts desired		
21.		Equipment cost or <b>#22 to #26</b>	\$	
22.		Production rate		
23.		Permanent equipment cost		
24.		Time load		
25.		Write off time		
26.		Overhead cost rate		
27.		Overhead cost or <b>#28 to #29</b>		
28.		Overhead cost rate		
29.		Production rate		



30.		overall cost (other) or #31 to #36		
31.		Warranties cost	\$	
32.		Cost of maintenance and repair	\$	
33.		Direct overhead cost	\$	
34.		Indirect overhead cost	\$	
35.		Depreciation cost	\$	
36.		Insurance cost	\$	
37.		Cost-effectiveness of remanufactured product and a new product or #38 and #39		
38.		Life cycle cost of a new product or #40 to #42	\$	
39.		Life cycle cost of the remanufactured product or #40 to #55	\$	
40.		New product acquisition cost	\$	
41.		Exploitation cost	\$	
42.		Disposal cost	\$	
43.		Life cycle cost from user's perspective or #44 to #48	\$	
44.		Used (remanufactured) product acquisition cost from users' perspective		
45.		Exploitation cost	\$	
46.		The cost associated with insurance, license, and fee	\$	
47.		Disposal cost	\$	
48.		Salvage value	\$	
49.		Used product acquisition cost from remanufacturing perspective	\$	
50.		New spare parts cost	\$	
51.		Cost of cleaning parts	\$	
52.		Cost of Labor	\$	
53.		Transportation cost	\$	
54.		Packaging cost	\$	
55.		Other manufacturing costs	\$	
56.	INDIRECT	Impact of infrastructure investment and services for public benefit through commercial, in-kind, or pro bono engagement.		
57.		Indirect economic impacts Jobs created by suppliers of the product or raw material.		

Table B.3 Social dimension

SNo		Data type / name	Measure	Process
1.	EMPLOYMENT	Complaint reports on the product from employees.		
2.		Required knowledge, skill and competence.		
3.	OCCUPATIONAL HEALTH, SAFETY	Injury incident or #4 and #5		
4.		Injury incident rate		
5.		Process time	hours	
6.		Lost working days or #5 and #7	days	
7.		Lost working day rate		
8.		Illness incident or #5 and #9		
9.		Illness incident rate		
10.		health impact of chemical C or #11 and #12		
11.		Daily risk of health damage from exposure to chemical, c		
12.		Persistence of chemical c in the environment		

13.	PSS LABELING	<p>PSS information</p> <p>Values can be given either 0 or 1 depending on availability or the following items of PSS information.</p> <ul style="list-style-type: none"> <li>• Architecture.</li> <li>• Relation between parts.</li> <li>• Life cycle cost.</li> <li>• Environmental load.</li> <li>• Emission information.</li> <li>• Energy consumption during use.</li> <li>• Discomforting effect.</li> <li>• Hazardous material content.</li> <li>• Service life.</li> <li>• Disposal strategy (recycling, etc.)</li> </ul>		
14.		<p>Customer satisfaction can be evaluated concerning;</p> <ul style="list-style-type: none"> <li>• Safety</li> <li>• Comfort</li> <li>• Value vs cost</li> <li>• User-product relationship</li> <li>• End-user satisfaction</li> </ul>		
15.		<p>Public trust through</p> <ul style="list-style-type: none"> <li>• Producing, protecting and strengthening product brand.</li> <li>• User-product relationship.</li> <li>• Values given by users.</li> <li>• Product responsibility regulation.</li> </ul>		
16.		designers design a product based on experience but it is necessary to check users' expectation		
17.	MARKETING	<p>Marketing benefit evaluation:</p> <ul style="list-style-type: none"> <li>• Focus on market.</li> <li>• Increasing trend in customers.</li> <li>• Frequency of repurchasing or demand.</li> </ul>		
18.	COMPLIANCE	finances – monetary		
19.		sanctions – nonmonetary		

### C. Article 1 (Published)

Title: Sustainability performance indicators for additive manufacturing: a literature review based on product life cycle studies

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## Sustainability performance indicators for additive manufacturing: a literature review based on product life cycle studies

[Getasew Taddese](#) , [Severine Durieux](#) & [Emmanuel Duc](#)

[The International Journal of Advanced Manufacturing Technology](#) **107**, 3109–3134(2020) | [Cite this article](#)

## D. Article 2

Title: Application of Multicriteria Decision Making Methodology for sustainability evaluation of Faceshield bracket manufacturing

Status: Ready for published

### Application of Multicriteria Decision Making Methodology for sustainability evaluation of faceshield bracket manufacturing

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#### Abstract

The unprecedented outbreak of Coronavirus at the beginning of 2020 created acute shortages of several medical equipment mainly personal protective equipment. This motivated several companies to manufacture these equipment from locally available resources. Faceshield brackets are among the many simple looking but highly relevant products manufactured in various workshops, including Sigma Clermont. However, many products have not been checked for appropriateness in design, quality, safety, comfort, and overall sustainability performance which might lead to unknown damages to human health and the environment. Thus, the main objective of this study is to evaluate sustainable performance of manufacturing of faceshield bracket using three manufacturing methods: injection molding, 3D printing and Laser cutting. Necessary data is collected through measurements from products, discussion with designers and machine operators, and supplementary data is utilized from experts' opinion and literature survey.

For the environment dimension, 3D printing showed better sustainability performance for energy (score = 0.041), emission, effluent and waste (score = 0.006), and transportation (score = 0.027) whereas laser cutting subcriteria of material (0.038) and injection molding showed better performance for subcriteria of conformance (0.006) and transport (score = 0.035) respectively. For economic dimension, injection molding shows better performance for indirect economic impact (score = 0.060) while 3D printing showed better performance for subcriteria of economic viability (score = 0.151) and marketing presence (0.016), respectively. For social dimension, injection molding shows better sustainability performance for four of the five subcriteria; employment (score = 0.058), occupational health and safety (score = 0.062) training and education (score = 0.027) and product and service labeling (score = 0.010) while 3D printing showed better performance for the remaining subcriteria of governance (score = 0.007). With respect to each dimension of sustainability, 3D printing (score = 0.108) showed better performance for environment, injection molding showed better economic and social performance with scores of 0.1922 and 0.160 respectively. Finally, overall performance has been assessed using total sum approach and Borda count methodology and injection molding showed better sustainability performance in the manufacturing of faceshield brackets with scores of 43 and 87 respectively.

#### Keywords

Faceshield bracket, injection molding, 3D printing, laser cutting, Analytic Hierarchy Process, Covid-19

## E. Courses / Trainings

SNo.	Course title	Medium of instruction	Key objectives / Skills	Status
1	'Ethique et intégrité scientifique' /  Research Ethics and Scientific integrity	French	<ul style="list-style-type: none"> <li>Know the values and concepts of ethics of research, ethics, and scientific integrity.</li> <li>Identification and prevention of cases of breach of scientific integrity</li> </ul>	Completed
2	Enseignement du français pour les doctorants étrangers /  Teaching French for foreign Ph.D. students	French	60 hours of a French language course at Alliance Ethio-Francaise in Addis Ababa (Level A1.1)	Completed
		French	20 hours of a language course at SIGMA Clermont with Mme RETAT Claire	Completed
		French	60 hours of a French language course at Alliance Ethio-Francaise in Addis Ababa (Level A1.2)	Completed
3	Increase Ph.D. employability through advanced and innovative approaches from strategy consulting	English	<p>Increase Ph.D.'s employability by using and adapting specific professional approaches coming for the strategy consulting sector</p> <ul style="list-style-type: none"> <li>What Ph.D. have to know about the job market and the way to contact their target firms accordingly.</li> <li>Advanced job interview techniques.</li> <li>Advanced techniques of management and problem solving inspired from the most prestigious management consulting firms</li> </ul>	Completed
4	Research funding: calls for projects /  Le financement de la recherche : appels à projets	English	<p>Understand the functioning, at the national and European level, of research funding through calls for projects,</p> <ul style="list-style-type: none"> <li>Acquire project development methodologies,</li> <li>Be able to identify funding opportunities,</li> <li>Better knowledge of existing research support structures.</li> </ul>	Completed
5	Marketing Analytics	English	<p>Course certificate achieved from University of Virginia through Coursera</p> <p>Skills:</p> <ul style="list-style-type: none"> <li>Marketing Experiments, Customer Lifetime Value, Regression Analysis, Marketing Analytics, and Brand Equity</li> </ul>	Completed
6	<p>Project Management &amp; Other tools for career development</p> <p><b>Course certificates:</b></p> <ul style="list-style-type: none"> <li>Initiating and planning projects</li> <li>Managing project risks and changes</li> <li>High-impact business writing</li> <li>The art of negotiation</li> </ul> <p>Effective problem-solving and decision-making</p>	English	<p>Course certificate achieved from University of California through Coursera</p> <p>Skills:</p> <ul style="list-style-type: none"> <li>Project Management, Risk Management, Communication, Negotiation</li> <li>Project planning, Change control, Change management, Proofreading and, Business writing</li> </ul>	Completed
7	Research integrity in scientific professions offered at FUN MOOC by Université de Bordeaux	English	<p>The objective of this training is to disseminate a culture of research integrity within institutions. Rather than passing on knowledge (this is not a learning process), it is a matter of raising awareness of the various issues associated with research integrity and encouraging a critical approach by proposing the basic elements necessary to understand and support the requirements of research integrity. This training aims at:</p> <ul style="list-style-type: none"> <li>Inform you about research integrity issues,</li> <li>Alert you to the mechanisms that can lead to scientific misconducts,</li> <li>Encourage you to develop a sense of responsibility and conduct yourself in a spirit of scientific integrity.</li> </ul>	Completed
8	Computational Geometry - Theory to Applications	English	<ul style="list-style-type: none"> <li>Introduce a large set of tools from theoretical background to at least one of its practical application (Computer Graphics with Blender)</li> </ul>	Completed
9	Introduction to programming with Matlab	English	<p>Course certificate achieved from Vanderbilt University through Coursera</p> <p>Skills:</p> <ul style="list-style-type: none"> <li>Computer programming, Problem-solving, Matlab, Programming language</li> </ul>	Completed
10	Introduction to Sustainability	English	<p>Course certificate achieved from University of Illinois through Coursera</p> <p>Skills:</p> <ul style="list-style-type: none"> <li>Sustainability theory and practice.</li> <li>Population, ecosystem, global change, energy, agriculture, water, environmental economics and policy, ethics, and cultural history</li> </ul>	Completed

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