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Analysis and modeling the intersection of Design for X techniques, Business strategies and Product Life-cycle Management

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Abstract. In today's dynamic digitalization environment, companies must continually seek to make improvements while still retaining their current position. This requires the use of new sustainable models that will ensure design efforts, addresses customer and societal needs during the entire product lifecycle phases (PLC). To succeed in improvements Design for X (DFX) requires addressing these issues across multiple factors X's that generates value for each stakeholder in the value chain. However, a variety of DFX techniques have been developed which makes the practitioners and researchers facing great difficulty to decide which techniques to use in which PLC phase to ensure which business strategy. In this respect, the aim of this paper is first to present a review of the most used and applicable DFX techniques to the sustainability dimension and PLC phases. Then, to define the hierarchical structure of the relationships among the identified DFX techniques and to analyze the characteristics power of each one, "interpretive structural modeling" (ISM) and MICMAC are implemented. The proposed framework would be useful for academics and practitioners because it demonstrates the interrelationships of DFX techniques and also offers an additional viewpoint for handling these techniques using the integrated ISM-MICMAC approach. The major implications and limitations are discussed.

Keywords: Sustainability, Design for X, Product Lifecycle Management, Business strategy, ISM, MICMAC.

1 Introduction

Globalization and digitalization have been causing a major shift in the global economy in recent years [1–3]. Many companies have sought to improve sustainable product design practices by focusing on not only economic targets but also environmental and social issues [4]. In fact, during the early stages of a project, improvements can be interpreted as opportunities for incremental product development, which can lead to innovation [5]. In this regard, Design For X (DFX) plays a critical

role in promoting sustainable product design from upstream to downstream operations, among various sustainable product design practices [6, 7]. The DFX techniques are used to enhance product design as well as the design process from the X perspective [8]. Across the year, more than 50 DFX techniques have been evolved beyond manufacture and assembly (DFMA) to the global supply chain (DFSC) with the updated implementation for various domains, taking into account the effect of the environment (DFE), serviceability (DFSv), quality (DFQ), and safety (DFS) in the product lifecycle (PLC) phases [7].

To deal with such issue and motivated by the fact that the PLC phases have a significant effect on the decision on which DFX techniques to use, Arnette et al., (2014) have developed a design for sustainability framework to incorporate the relationship between DFX techniques and PLC phases as well as product differentiation and cost leadership strategies [6]. After that, Benabdellah et al., (2020) provided a relationship between different DFX techniques and PLC phases as well as a classification of them according to common benefits such as the reduction of cost production and variation and defects strategies. The authors have also used the Analytical Hierarchy process to connect DFX techniques with IATF quality attributes to satisfy customers' requirements[3] in automotive industry.

Among the research developed, no paper has been focusing on the relationship between DFX techniques using a multi-criteria decision-making strategy. To fill this gap, this study aims to look into the contextual relationships between various DFX techniques and prioritize them using the Interpretive Structural Modeling (ISM) methodology. One of the key advantages of using ISM is that it converts the conceptual model into a measurable and organized model that can be used to place and prioritize DFX techniques[9]. Parallel to the use of ISM, other methodologies such as ANP (Analytic Network Process), TOPSIS, and AHP (Analytic Hierarchy process) were considered[10]. Since they are quantitative methodologies that would make the proposed framework more complicated and difficult to reproduce, they were omitted. However, as ISM produces a hierarchical graph, it's necessary to decide which of the DFX techniques have a higher or secondary impact[9]. To do so, MICMAC analysis is used.

The article is organized as follows: Section 2 presents basic terminologies needed to prepare the groundwork of this study. Section 3 shows the methodology used in this paper. Section 4 studied the relationships between DFX techniques, PLC phases, and strategies undertaken by companies. Section 5 provided the ISM-MICMAC for DFX techniques. Section 6 illustrates the implications for both practitioners and researchers. Conclusion and future works are drawn in the final section.

2 Research Background

2.1 Product development process

In the literature, there is not a unified definition of the product development process (PDP). Thus, an analysis of the different definitions found in the literature shown that "PDP allows making decisions at the right time, to avoid design and manufacturing

problems. It can also save time as it avoids backtracking, helps to minimize financial risks through a goal validation system, and increases the chances of getting to market at the right time by controlling development time”[5]. Thus, PDP emphasizes the multidisciplinary aspect to meet customer requirements. Besides, the implementation of this process is conditioned by the commitment, integration and collaboration of all the different areas of expertise throughout the whole life cycle of a product. In this regard, outside of the Product Lifecycle Management (PLM) approach, PDP cannot be considered [11].

“PLM is about how to organize product development, manufacturing and support in the way that will make your product a first-class citizen”[3]. Several researchers and practitioners have suggested categorizing the product lifecycle into three major categories to follow a clear model of use: the beginning of life (BOL), the middle of life (MOL) and the end of life (End of Life) (EOL)[3, 12, 13]. In this paper, the product lifecycle is categorized into five value chain to BOL, MOL, and EOL (Fig.2): (1) BOL includes Feasibility, Design, and logistics value chain; (2) MOL includes Service value chain; and (3) EOL includes Reverse logistics value chain.

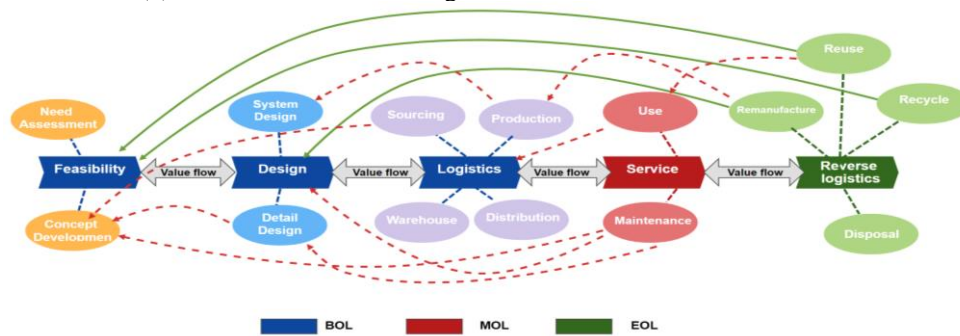


Fig. 2. Value chain of product lifecycle.

In general, the complexity of products is increasing, while the development time and the lifespan of products are decreasing. The design phase, at the start of the product life cycle, appears eminently strategic, and in particular, it's very upstream phases as it involves many experts with different skills [14]. Indeed, it is during this phase, which generally only consumes around 5 to 10% of the product cost, that the vast majority of the characteristics and behaviors of the future product, as well as its production process, are determined and decided. Thus 80% to 95% of the life cycle is practically defined at the end of the design phase, any modification subsequently made to the product to reduce certain costs is particularly expensive or ineffective, or even both [5].

2.2 Design for X

Technological and computing advances have led to a rapidly changing environment in recent decades. In this respect, diverging markets, product and process complexity, digital demand, and cost pressure are the new challenges that companies have to face to compete effectively [7]. However, the reality of the new PDP requires a much more

realistic approach by using methodologies to meet the changing of the customer, manufacturers and government regulatory requirements [3, 6]. To deal with these issues, several design techniques have been developed leading to the Design for X (DFX) umbrella term. The specific perspective represented by X refers to a specific virtue or life-cycle phases [3, 7, 8]. Furthermore, the DFX approach is employed to improve product design as well as the design process from the specific perspective represented by X.

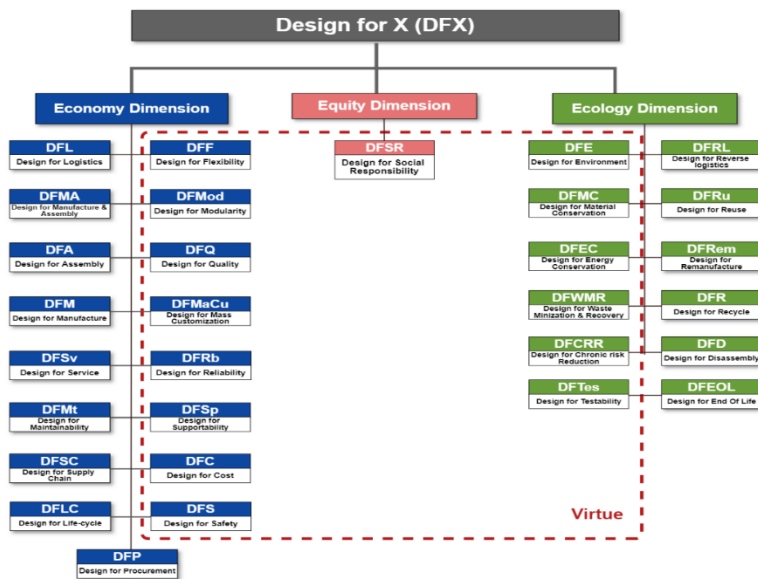


Fig. 3. Design for X taxonomy according to sustainable dimension

The initial "Design for" methods were designed to make the organizational and manufacturing aspects of product development more effective and to minimize costs, time, and mistakes. To proactively handle these production problems, DFX techniques such as "Design for Manufacture" (DFMA), "Design for Supply chain" (DFSC), and "Design for Quality" (DFQ), were developed [7]. After that, Managers, researchers, and engineers recognized that through enhanced product design, many environmental challenges could be reduced, leading to new DFX approaches such as "Design for Recyclability" (DFR), "Design for remanufacture" (DFRem), and "Design for environment" (DFE)[4]. More recently, concerning the equity dimension, other DFX techniques, namely "Design for Social Responsibility" (DFSR) appear to provide opportunities for society[6]. By considering all these integrated DFX techniques, we implement the ideas of the Triple Bottom line and evaluated the sustainability while developing a product. Figure 3 illustrates the main DFX techniques found in the literature from 1980 to 2019 according to the three sustainable dimensions that are economy, ecology, and equity[7]. In terms of the perspectives of the X, which can be a virtue or a lifecycle, the techniques were also classified.

3 Research Methodology

This study aims to establish which DFX techniques are most useful during the design process, as well as the relationships and trade-offs that occur between design decisions made during the different stages of the product lifecycle. Mixed investigative methods are used to answer the research questions.

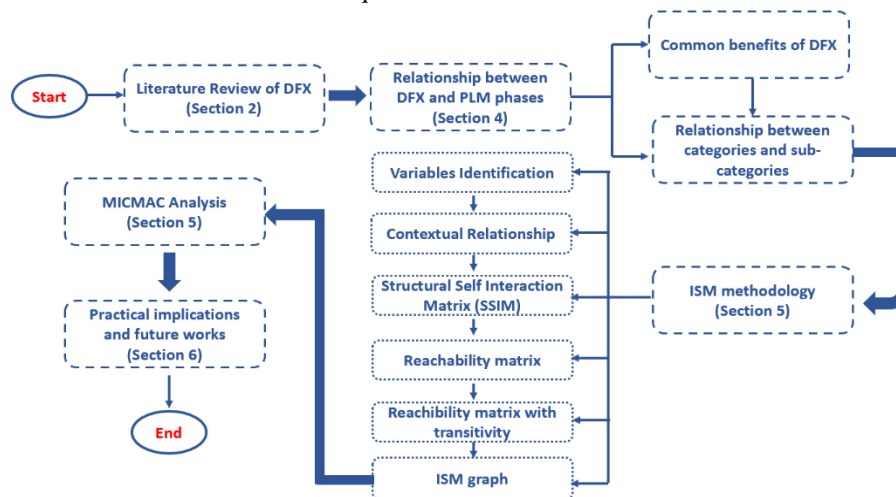


Fig. 4. The methodological process followed in the study

According to the conceptual map, we give first an overview of the main DFX techniques used in the literature from various databases such as Emerald, IEEE, Scopus, Taylor & Francis and Google Scholar (Benabellah et al 2019). As shown in section 2, we have a plethora of DFX techniques that have been established and proposed over time. therefore, the questions such as which one to implement in which lifecycle phase need to be answered. To do so, in the second step, the relationship between the DFX techniques and the product lifecycle phases is shown. Third, according to the typical benefits (“Cost leadership” or “product differentiation”), we identify the needed DFX and for the chosen ones, we analyze the potential relationships and trade-offs and determine the principal ones. Through the ISM and MICMAC analysis, the established techniques are deeply evaluated. The goal of using such multi-criteria decision methods is to look at how DFX interact with each other and describe and summarize their contextual relationship in a hierarchical manner. In this regards, five steps are involved:

- Contextual relationships are formed between attributes for which pairs of attributes are examined.
- Structural Self Interaction Matrix (SSIM) is formed, which indicates pair-wise relationships between the DFX techniques under consideration.
- Binary Matrix is obtained first converting the SSIM matrix and a reachability matrix is formed by considering transitivity properties that state that if an

attribute A is associated with B and B is associated with C, then A is related to C.

- The reachability matrix is partitioned into different levels and transitive links are removed allowing to obtain a digraph.
- The resulted digraph is converted into an ISM by replacing attribute nodes with statements and it is then checked for conceptual inconsistency.

Once the ISM hierarchical model is obtained, we then use the MICMAC analysis to evaluate the DFX techniques' driver and dependency strength.

4 Classification of DFX techniques with Product Lifecycle phases

Research studies have strengthened our understanding of different design problems for more than 30 years and enhanced decision-making processes[3]. For this purpose, several DFX techniques across many disciplines have been developed. In this respect, the decision about which DFX method to apply is directly affected by the phases of the product life-cycle as well as the strategies considered by companies [3, 6]. Concerning the PLM process, some DFX techniques are used in the wrong phase while other ones are not properly implemented [15].

Several researchers have tried to relate DFX techniques with only the design process rather than the entire lifecycle [16, 17]. Other ones have considered DFX techniques that were insufficient and did not recognize the entire lifecycle [6]. Recently, benabdellah et al, (2020) have categorized more than 37 DFX techniques into product lifecycle phases[3]. Following the same reasoning, Fig.5 presents a categorization of the most applicable DFX techniques while considering the lifecycle categorization presented in section 2. In addition, to connect DFX techniques to lifecycle phases, there is a need to relate them with adequate business strategies. In general, “a strategy is defined as the business-level decision mechanism that should guide competitive decisions to one product or a family of products” [18]. In this respect, there are two key strategies considered in the literature: (1)“Cost leadership” that aims to minimize cost in the whole PDP; and (2)“Product differentiation” that aims to satisfy consumer needs based on features or service[18]. According to Benabdellah et al, (2020), the strategies are breaking into many sub-categories to better understand them and improve their performance. For the “cost leadership”, the business strategy has been decomposed into three sub-strategies that aim at reducing the cost of supply chain, production and ownership [7]. For the “product differentiation”, the business strategy has been decomposed into two sub-strategies that aim at reducing environmental effect and variation and defects [7]. By considering the two categories and subcategories and following the same methods as considered by [7], we added three other subcategories such as reduction of barriers to innovation, reduction of failure and lifecycle rate.

developing a product, we use a graphic adapted from[3] to understand the relationship between DFX techniques. The broader techniques are depicted as squares while subcategories are represented as circles [3].

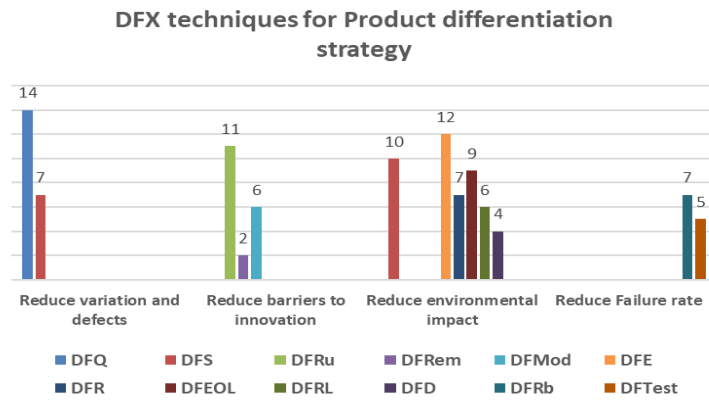


Fig. 7. DFX classification according to product differentiation strategy

Fig.8 illustrated the relationship between the 30 studied DFX techniques. DFSC and DFE, for example, influence each other, so DFMA and DFL are influenced by and have an effect on DFE goals. Based on this analysis, we can argue that instead of considering 30 DFX, we can simply consider the wider categories that are DFMA, DFLLC, DFC, DFQ, DFS_v, DFSC, DFL, DFS, DFE, DFRL and DFEOL. Design for life-cycle (DFLLC) was excluded from the table as many of the other DFX are related to life-cycle phases, making it redundant and design for cost (DFC) was not included as most, if not all other DFX, take cost into account.

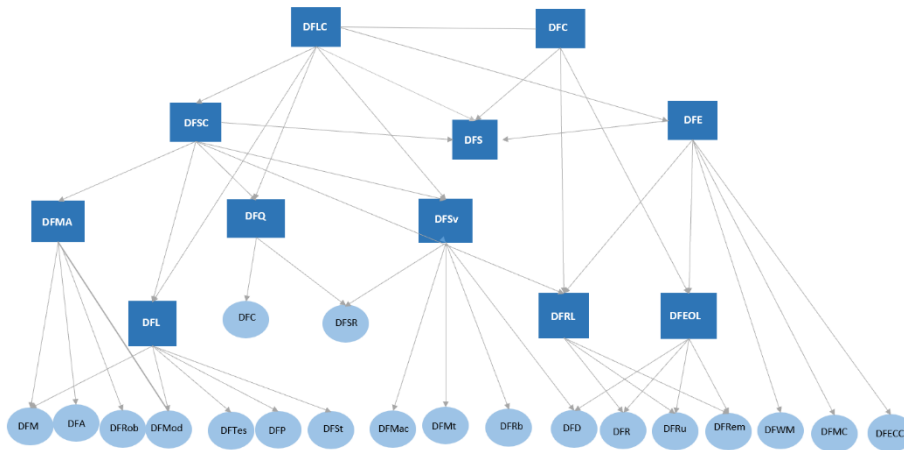


Fig. 8. DFX classification according to product differentiation strategy

In the next section, we are going to present a well-established methodology for the identification of the relationships between the considered DFX techniques using ISM and MICMAC method.

5 ISM-MICMAC approach for DFX techniques

ISM was proposed for the first time by J. N. Warfield [26]. It creates interrelationships of unstructured variables based on expert judgment making it a useful technique for defining and summarizing relationships among specific factors [9]. Besides, the basic concept behind ISM is to decompose a structure that is complicated into many subsystems, called elements, using experts' practical experience and expertise to create a multi-level structural model [27]. In this respect, as a common method for evaluating and approaching interrelationship attributes, techniques like AHP, DEMATEL, TOPSIS and DEA can also be used to evaluate multi-criteria decision [10]. However, by considering what makes a strong management operations theory, we can conclude that ISM is a methodology that is parsimonious and generalizable [10]. However, to decide which of the DFX techniques have a higher or secondary impact [9]. To do so, MICMAC analysis is used.

5.1 Data collection

The ISM approach involves a series of repeated interrogations of a group of experts whose opinions or decisions are of concern. Three experts (Design for Manufacture and Assembly specialist, Project Manager, and consultant and trainer in Quality Management) from various industries have validated all of these measures to create the contextual relationship between the 9 established DFX techniques. In other words, the experts were charged with deciding whether one technique led to another one. They examine and validate also the finding after defining the contextual relationship between the DFX techniques. Once the criteria (DFX techniques) for evaluating the interactions have been listed, the contextual relationship between them must be identified to create the “structural self-interaction matrix (SSIM)”.

5.2 Structural Self-Interaction Matrix (SSIM) and first reachability matrix

In the development of SSIM and the first reachability matrix, four symbols were used to denote the direction of relationship between the attributes (i and j)[27]. If the technique i affects/reaches/alleviates j, then we note V. In contrast, we note A, if the technique j affects/reaches/alleviates i. If the techniques are not related, then we note O. Whereas when the technique i and j affect/reach/alleviate each other, then we note X. Therefore, once the SSIM is obtained, we transform it into a binary matrix (first reachability matrix) by replacing V, X, A and O with the binary variables (1 or 0). More clearly, the initial reachability matrix (table 1) is obtained by following these rules. “If the (i, j) entry in the SSIM is V, then the (i, j) entry in the reachability matrix becomes 1 and the (j, i) entry becomes 0”. “If the (i, j) entry in the SSIM is A, then the (i, j) entry in the reachability matrix becomes 0 and the (j, i) entry becomes 1”. “If the (i, j)

entry in the SSIM is X, then both the (i, j) and (j, i) entries of the reachability matrix become 1". "If the (i, j) entry of the SSIM is O, then both the (i, j) and (j, i) entries of the reachability matrix become 0".

Table 1. Initial Reachability matrix

No	DFX techniques	1	2	3	4	5	6	7	8	9
1	DFMA	1	1	1	1	0	1	0	1	1
2	DFL	0	1	1	0	1	1	1	1	1
3	DFE	0	0	1	1	0	1	0	1	1
4	DFQ	0	1	0	1	0	1	0	1	1
5	DFSC	1	0	1	1	1	1	1	1	1
6	DFEoL	0	0	0	0	0	1	0	0	1
7	DFS	1	0	1	1	0	1	1	1	1
8	DFSv	0	0	0	0	0	1	0	1	1
9	DFRL	0	0	0	0	0	0	0	0	1

5.3 Final reachability matrix and level partitions

In the final reachability matrix, the fundamental assumption which is transitivity is used (denoted by 1*). This last state that if attribute A is related to B and B to C then, A is necessarily related to C [9]. Table 2 presents the final reachability matrix for DFX techniques that define the driven and dependence power of each technique. More clearly, the sum of interactions of the technique in the line, is its driving force, while the sum of interactions in the columns, is the dependence power.

Table 2. Final Reachability matrix

No	DFX techniques	1	2	3	4	5	6	7	8	9	Drive power
1	DFMA	1	1	1	1	1*	1	1*	1	1	9
2	DFL	1*	1	1	1*	1	1	1	1	1	9
3	DFE	0	1*	1	1	0	1	0	1	1	5
4	DFQ	0	1	0	1	1*	1	1*	1	1	7
5	DFSC	1	1*	1	1	1	1	1	1	1	8
6	DFEoL	0	0	0	0	0	1	0	0	1	2
7	DFS	1	1*	1	1	0	1	1	1	1	8
8	DFSv	0	0	0	0	0	1	0	1	1	3
9	DFRL	0	0	0	0	0	0	0	0	1	1
Dependency power		4	6	5	5	4	8	5	7	9	

Once the final reachability matrix is obtained, to classify the DFX techniques into levels, we organize the elements according to their levels based on their antecedent and

reachability index, the reachability matrix is transformed into a canonical matrix format. By doing so, the first level has the max number of the antecedent, once it is established it is removed from the matrix and the process is repeated until the last level is reached. Table 4 presents the final level classification of DFX techniques.

Table 4. Level partitions of DFX techniques.

Level partition	DFX techniques	No
I	Design for Reverse logistics (DFRL)	9
II	Design for End of Life (DFEOL)	6
III	Design for Service (DFSv)	8
IV	Design for manufacture & assembly (DFMA)	1
	Design for logistics (DFL)	2
	Design for Supply Chain (DFSC)	5
V	Design for Safety (DFS)	7
	Design for Quality (DFQ)	4
VI	Design for Environment (DFE)	3

5.4 ISM-MICMAC proposed model for DFX techniques

The structural model is developed using the final reachability matrix. Each element in its level, as well as relations between them, are represented in the digraph[10]. Following that, we removed transitivity from the model and replaced each ID node with the definition that corresponded to it. Finally, we tested the model for any conceptual inconsistency. Figure 9 shows the hierarchical proposed model for DFX techniques.

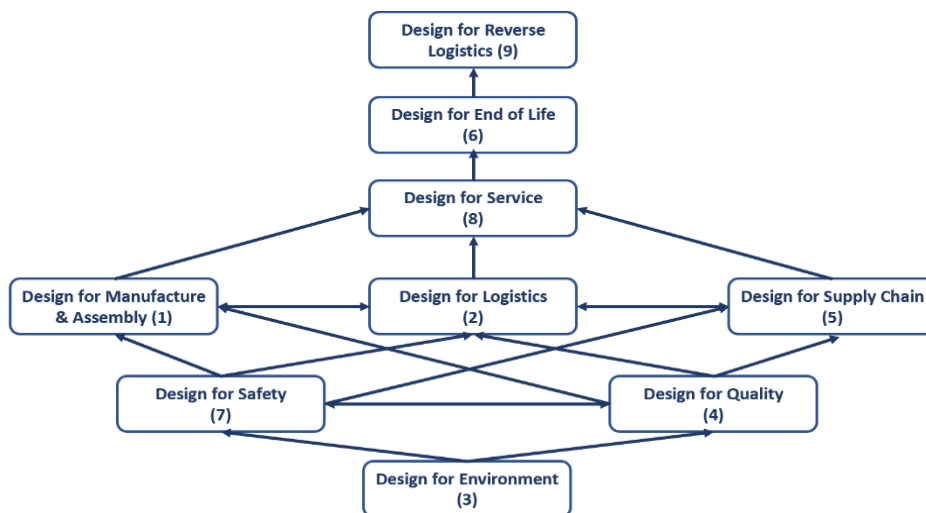


Fig. 9. ISM hierarchical based model for DFX techniques

According to the proposed hierarchical-based model of the ISM, we can remark that Design for Environment (3) is one of the most important techniques that influence the sustainable PDP. The second is Design for quality (4) and Design for safety (7). The third ones are Design for Manufacture (1), Design for Logistics (2) and Design for Supply Chain (5) which have the same importance and influence. The fourth is Design for Service (8) and the less influential technique to drive design process activity is Design for Reverse logistics (9) followed by Design for End of Life (6). With respect to the obtained results, the effectiveness of PDP should start with the consideration of virtues such as environment, quality and safety because it can affect other techniques such as manufacture, assembly, logistics, supply chain, service and end of life. In addition to that, the relationship between these techniques encompasses the basic principle of the product lifecycle phases, which start with product development and end with product disposal. Furthermore, to specifically implement DFL or DFMA or DFSC it is essential to drive such technique coupling with both DFS, DFQ and DFE where their outputs affect each other. Similarly, to have a good DFSv, techniques including DFMA, DFL and DFSC should be integrated as their performance is related. Finally, the consideration of the seventh DFX (DFMA, DFL, DFSv, DFE, DFQ, DFS, DFSC) techniques can lead to a sustainable product with the end of life and reverse logistics cost, energy and time-saving. However, in addition to the obtained bigraph, it is important to provide details about the relative importance and interdependence of the various DFX techniques to find a wealth of knowledge. To do so, based on driver and dependency power, MICMAC evaluates each technique using an indirect classification scheme[9].

Drive power	9				1	2				
	8				5			III- Linkage		
	7		IV- Driving			4				
	6									
	5					3				
	4								II- Dependent	
	3		I- Autonomous					8		
	2					7			6	
	1									9
		1	2	3	4	5	6	7	8	9
		Dependency power								

Fig. 10. MICMAC analysis for DFX techniques

Figure 10 shows that there are no autonomous techniques that indicate the importance of the selected DFX techniques for this study. We notice that, as presented in section 4, to choose the prominent DFX techniques, we have categorized more than 30 DFX techniques according to the sustainability dimension. After that, we have presented the relationships between them and the PLC phases. The considered DFX techniques from this step have been also categorized according to strategies undertaken by companies.

To more simplify and reduce the number of DFX techniques, we have studied the relation between them and show the categories and subcategories. Among the ninth DFX technique, two techniques (DFMA and DFSC) are falling in the driving quadrant as they are techniques that have a high driving power and low dependency. This means that these techniques need to be controlled and managers and engineers must work hard to deal with them as they are the pillar of the PDP performance. Further, four techniques (DFS, DFSv, DFEoL and DFRL) consist of low driver power and strong dependency power. This means that these risks should be regarded as important techniques because their strong dependence can affect the whole PDP. While the others (DFL, DFQ and DFE) consist of high driving and dependency power. This means that these techniques are unstable and change with regard to different disruptions.

These findings complement the work of benabdellah et al, (2020) by evaluating not only the most prominent DFX techniques but which technique are more important than other one and which one influence the others[3]. Besides, we indicate the cruciality of each DFX technique to the fourth category of MICMAC analysis. By doing so, the proposed ISM-MICMAC hierarchical model would assist companies' decision-makers in efficiently planning their operations through the PDP. In the next section, key implications for both practitioners and researchers are presented.

6 Practical and theoretical implications

In this article, the ISM-MICMAC methodology has been made to expose DFX techniques interdependencies. Managers may use the approach to create a map of the dynamic between different factors in a decision-making process. The pairwise technique analysis in a community of experts from various areas invites input from those who are familiar with the issues being addressed but may not be familiar with all of the relevant issues to the overall PDP. From a theoretical point of view, the proposed model will first decompose complex structures into a multi-level hierarchical model and provide such a fundamental understanding of DFX techniques interrelation and influence. Second, this research offers a thorough overview of the most important DFX techniques for achieving long-term sustainability. Third, it serves as a reference for researchers who are new to DFX techniques to discuss this study and focus on the potential issues. Fourth, this paper contributes to sustainability design by investigating crucial DFX techniques and gaining better insights into economic, environmental, and social studies issues. From a practitioner's standpoint, the current model first will assist decision-makers in understanding the mutual impact among different DFX techniques and their implications for design strategy decisions towards organizational efficiency. Second, by effectively implementing the identified DFX techniques, it can assist managers and designers in focusing their efforts toward achieving high organizational efficiency. Third, it will also assist in achieving sustainability operations and improving the PDP's economic efficiency. Finally, this research represents a major step forward in design research at the intersection of service, safety, quality, assembly, supply chain, reverse logistics and environmental considerations, as well as a wider method of combining these factors.

7 Conclusion and future works

Designing a product with various X factors is a complex task that requires a holistic approach. Structural, economic, human, social, and environmental factors must all be addressed. The use of DFX techniques will help a company's competitiveness while lowering environmental and economic risks for a successful, sustainable process in the PLC phases. Several important contributions to the existing body of knowledge to link manufacturing products to sustainable outcomes have been made as a result of this research.

First, this paper contributes in this regard by providing practitioners with a structure for determining which DFX techniques are appropriate for a given product design based on strategy and life-cycle process. Second, it shows the relation between DFX techniques in terms of categories and sub-categories. In this respect, instead of considering all these techniques to achieve sustainability outcomes, we can simply consider the wider categories that are DFMA, DFLC, DFC, DFQ, DFS_v, DFSC, DFL, DFS, DFE, DFRL and DFEOL (Fig.8).

Third, this article uses an ISM-MICMAC approach to examine the interdependencies among DFX techniques to better understand their mutual influences and thus better manage the PDP. This approach aids in understanding the interactions among techniques by using a hierarchical graphical model. Fig.9 shows that Design for Environment (3) is one of the most important techniques that influences the sustainable product development process. The second is Design for quality (4) and Design for safety (7). The third ones are Design for Manufacture (1), Design for Logistics (2) and Design for Supply Chain (5) which have the same importance and influence. The fourth is Design for Service (8) and the less influential technique to drive design process activity is Design for Reverse logistics (9) followed by Design for End of Life (6).

Fourth, combining ISM and MICMAC analysis allows DFX techniques to be classified into four categories: autonomous, linkage, dependent, and independent. As a result, the criticality rating of DFX can be determined based on their direct and indirect dependencies on one another. It has been presented in Fig 10 that there are no autonomous techniques, while DFMA and DFSC are driving techniques that need to be controlled as they are the pillar of the PDP performance. In contrast, DFS, DFS_v, DFEoL and DFRL are dependent techniques that can affect the whole PDP. Finally, the DFL, DFQ and DFE are unstable techniques to different disruptions that affect the PDP.

There are some drawbacks to this paper that provide opportunities for future research. First, the ISM model can be also used in a fuzzy manner to improve binary ISM. Second, the indices are based on expert judgment, the metaheuristic method can be used for data collection to reduce the mistakes of decision-makers and experts. Third, the proposed ISM-based hierarchical model could be verified using Structural Equation Modeling (SEM). Finally, multi-criteria methods such as fuzzy-AHP, TOPSIS, ANP, and fuzzy-DEMATEL can be used or combined to test the defined techniques, and the results can be compared.

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