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A Collaborative Scheme for DFX Techniques in Concurrent Engineering Mitigated with Total Design Activity Model

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ABSTRACT
Industry 4.0 has sparked rapid changes in the manufacturing and construction sectors, leading to a significant shift in how off-site factory-based panelized construction machines are designed and manufactured. Concurrent engineering which seeks to close the gap between design and manufacturing sectors provides an ideal environment for machine development. It is a systematic methodology to integrate machines holistic concurrent design activities and their related processes. Competition arising in the marketplace for newly developed machines is driving modifications in the way machine designers develop production machines. Thus, to boost the efficiency in concurrent machine development, appropriate evaluation, and decision analysis tools required to be developed and utilized. Currently, there is no DFX selection tool available to aid the designer in concurrent machine design applications. In this paper, these challenges are addressed through a comprehensive qualitative literature review of DFX techniques with their implementation in Stuart Pugh: Total Design Activity Model. Various DFX techniques are mapped and clustered in a collaborative scheme, interactions and links between them are identified, and the relative importance weight of each is calculated. A description of a functional DFX scheme is proposed in this paper that can aid designers in establishing lean design processes for machine development and reveals its potential application in Multi-DFX fuzzy multi-criteria decision-support system.

KEYWORDS
Industry 4.0; Concurrent Engineering; Design for X; Total Design Activity Model; Multi-DFX.

INTRODUCTION
Research conducted by Guangleng and Yuyun (1996) has concluded that the early design stages of the machine development process are the most influential determinant of machine total cost. By contrast, prototyping, production, manufacturing, and maintenance considerations contribute to a higher percentage of the total machine cost. Concurrent engineering (CE) aims to exploit opportunities for machine design improvements at each phase of the machine lifecycle by integrating machine design and their related process development so that the percentage of the redesign is minimized. The success of the machine design depends on the accuracy of design decision making. Also, in the early phases of machine development, the production cost is minimized when accurate decisions are implemented. CE offers the designer the ability to select multiple design decision tools spanning all production processes, which can widen the designer's

technical overview of the machine development stage. However, poor tool selection may lead to deficiencies in machine development time, quality, and cost (Ahmad et al., 2014). The main difference between traditional and CE is that the latter regard machine development as an integrated, systematic, and concurrent process of continuous improvement. A significant challenge of CE is to make correct decisions at the early stages of machine development when committed costs are still low, and design information is vague. Therefore, in CE the design activities costs are higher in the early stages of machine development. However, compared with traditional sequential engineering, development times are shorter, and thus the total cost is lower. Figure 1 illustrates the cost impact of CE, as explained by Veryzer (2005), of the machine value of design throughout each product development stage. Although the shortcomings of sequential traditional engineering and the advantages of CE in machine development are well established in the literature, though, as discussed by Fujimoto and Clark (1991) and by Clausing (1993), the transformation from a problem-prone sequential engineering paradigm to a problem-free CE environment remains a challenge.

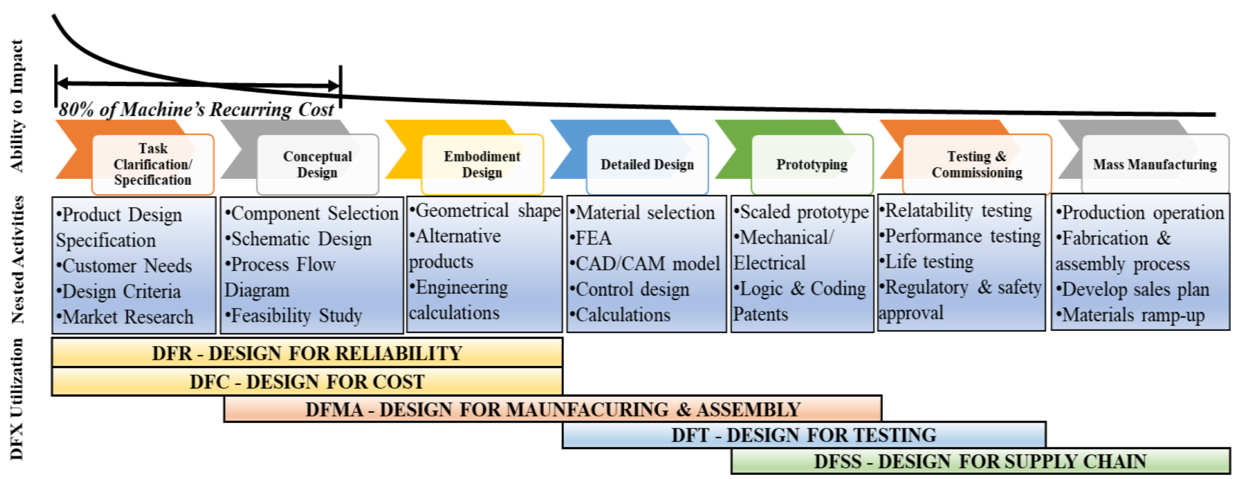

Figure 1. Machine Development Stages

The general purpose of implementing CE as explained by Guangleng and Yuyun (1996) in the machine design development is to improve quality, reduce cost and cycle time, and increase flexibility, productivity, and efficiency. It is intended to stimulate designers to consider all elements of the machine lifecycle in the early stages of the design. Figure 2 represents the machine design model in CE and explain the link between the design elements and the process. Numerous methods and tools have been developed to ease the implementation of CE in machine design. Among these methods is Design for X (DFX) techniques, where X stands for a specific life phase (e.g., manufacture, assembly) or virtue that the machine should possess (e.g., quality). However, these methods are usually not standardized, and in most cases, they have contradicting rules and results between them if applied in a design problem. Designers can achieve design goals, explore constraints, overcome difficulties, and consider the ramifications of their decisions early in the machine lifecycle when DFX techniques are implemented (Ahmad et al., 2014). The main DFX functionality accomplished by DFX techniques and their users' "designers" is summarized in Figure 3 where the first four functions and the second five functions are carried out mainly by designers, although few of these functions are achieve by them to some extent.

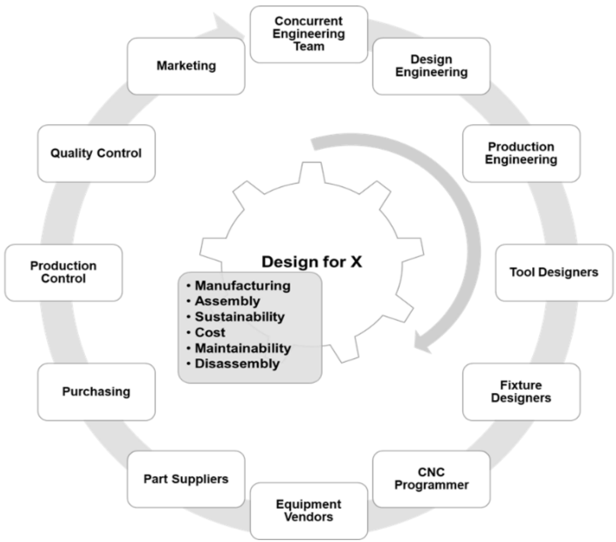

Figure 2. Machine Design Model in CE

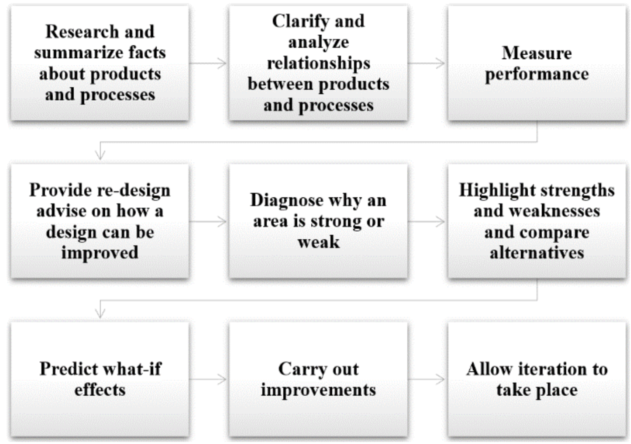

Figure 3. Main DFX Functionality

METHODOLOGY

CE requires a holistic and systematic view of the machine design development process, so DFX techniques should be integrated and applied with a broader perspective and not applied in isolation. However, the relationships and interdependencies between DFX techniques and their links to the design process have garnered little attention in the literature. In this paper these challenges are addressed through a review of various existing DFX techniques with potential applications at different stages in the total product design activity model is conducted. Based on the conducted literature review, the research work includes: (1) Mapping and clustering of the DFX methods utilized in Stuart Pugh Model, (2) a scheme which describes the interactions, links and interdependencies among DFXs tools, and (3) the relative importance weight calculations of different DFX techniques to guide/aid designers in selecting the most applicable ones for implementation in machine design.

Mapping Existing DFX Techniques

The various DFX techniques related to this study are presented in this paper, and they are interrelated to various degrees. Research results are filtered and grouped with the main objective of generating a list of the most applicable DFX techniques related to machine design development and their characteristics from the literature. DFX techniques can be classified and arranged based on their: (1) purpose or goal, (2) scope, (3) character, and (4) focus. Figure 4 represents the DFX categorization map developed during this research to facilitate the literature review findings.

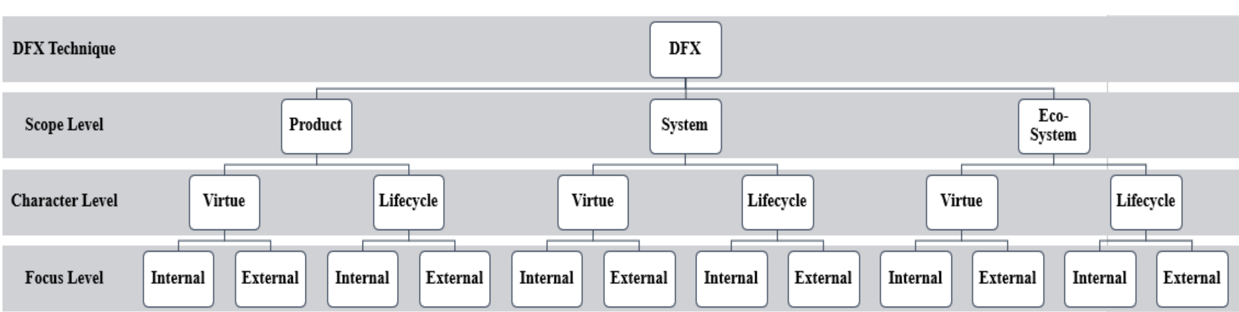

Figure 4. DFX Categorization Map

The scope of DFX implementation can span the product, system, ecosystem level, or a combination thereof (Chiu and Kremer, 2001). The product scope level focuses on the machine aspects which is an approach to designing a product such that the product design is instantly transitioned into production, manufactured at minimum cost with the highest quality (Chiu and Okudan, 2010). Fabricius (1994) proposed a set of general machine design guidelines to enhance the link between the design and manufacturing stages using a three-dimensional model. Different from the guidelines above, which are metric-based, Stoll (1988) described thirteen DFM guidelines that are strategy-based and practice-oriented. The system scope level focuses on the integration and manages the degree of coordination between different aspects of the machine value chain. The eco-system scope level referred to as green design, meanwhile, entails applying machine design engineering methodologies with the embodiment of a natural system to promote the effort in reducing greenhouse gases emissions.

Table 1. DFX Techniques Categorization

History and Overview of Design for X (DfX) Techniques											
DFX Application		**Stuart Pugh: Total Design Activity Model**					**Scope**	**Character**	**Focus**	**References**
Design For	**Main Objective**	**Specs.**	**Concpet**	**Detailed**	**Manufacture**	**Sell**				
Cost (DFC)	Minimize lifecycle costs	1,3	3,4,5	3,4,5	1,3,4,5	3	A,B,C	X	I	Unal & Dean (1992)
Manufacturing (DFM)	Minimize production costs	1,.3	1,2,3	1,3,4	1,3		A	Y	I	Stoll (1988)
Assembly (DFA)	Minimize production costs		3	3,4		3	A	Y	I	Nof et al. (1997)
Manufacturing & Assembly (DFMA)	Minimize production costs	1,3	1,3,4	1,3,4	1,3		A	Y	I	Boothroyd (1994)
Variety (DFV)	Minimize obstacles for inovation	3	3	3,5	3,5		A	X,Y	I	Martin (1999)
Quality (DFQ)	Maximize product quality	1	1,3,4	1,3,4,5	1,3,4,5	3	A	X	I,E	Franceschini & Rossetto (1997)
Six Sigma (DFSS)	Minimize variations and defects		1,3	1,3,5			A	X,Y	I	Harry & Schroeder (2000)
Quality Manufacturability (DFQM)	Improve product quality	1			1	3	A	X,Y	I	Das et al. (2000)
Reusability (DFRE)	Minimize obstacles for inovation			3		3	A	X	I	Cowan & Lucena (1995); Torroja et al. (1997)
Disassembly (DFDA)	Minimize environmental impact		1,3	1,3,5			A	Y	I	Zussman et al. (1994); Zhang & Kuo (1996)
Reliability (DFR)	Minimize failure percentage		1,5	1,5			A	X	I	Lalli & Packard (1994); Pecht (2007)
Testability (DFT)	Minimize failure percentage			1,3,4,5	1,3,4,5		A	X	I	Williams & Parker (1982); Pettichord (2002)
Obsolescence (DFO)	Minimize supply chain costs			3		3	A	Y	I	Singh & Sandborn (2006); Sandborn (2013)
Maintainability (DFMAI)	Minimize cost of ownership		2	2			A	X	I	Tortorella (2015)
Serviceability (DFSE)	Minimize cost of ownership		2	2			A	X	I	Dewhurst (1996)
Robustness (DFRO)	Minimize cost of production			1,3	1,3		A	X	I	Yu & Ishii (1998); Knoll & Vogel (2009)
End-Of-Life (DFEL)	Minimize environmental impact		1,3	1,3,4	1,3,4		A	Y	E	Allenby & Graedel (1993)
Remanufacture (DFRem)	Minimize obstacles for inovation			1,3	1,3		A	Y	I	Hatcher et al. (2011)
Failure Modes (DFMEA)	Minimize failure percentage	1,2	1,2,3				A	Y	I	Cutuli et al. (2006)
Material Substitution (DFMS)	Maximize resilience		1,3			4	A	X	I	Ljungberg (2005)
Modularity (DFMO)	Minimize obstacles for inovation			1,3		3	A	X	I	Erixon (1996)
Affordances (DFAF)	Maximize customer satisfaction	1,3,4	1,3			4	A	X	I	Maier & Fadel (2001)
User Empowerment (DFEM)	Maximize customer satisfaction	1,3,4	3,4				A	X	E	Ladner, R. E. (2015)
Lifecycle (DFLC)	Minimize lifecycle costs	1	1,3,4	1,3,4	1,3,4	1,3,4	B	Y	E	Chiu & Okusan (2010)
Transportability (DFTR)	Minimize supply chain costs			1,3,4		3	B	Y	E	Dowlatshahi (1999)
Mass Customization (DFMC)	Minimize obstacles for inovation	1,3,4		4,5	3,4,5	3	B	Y	E	Tseng & Jiao (1998)
Adaptability (DFAD)	Minimize obstacles for inovation			1,3,4			B	X	I	Gu et al. (2016)
Lean Six Sigma (DFLSS)	Minimize environmental impact		1,3	1,3,5	1,3		B,C	Y	E	Jugulum & Samuel (2010)
Sustainability (DFS)	Minimize environmental impact	1	1,3	1,3,4	1,3,4		C	X	E	Bhamra & Lofthouse (2007)
Recyclability (DFREC)	Minimize environmental impact		1,3	1,3,5			C	Y	E	Gaustad et al. (2010)
Energy Recovery (DFER)	Minimize environmental impact			1,3			C	X	E	Ljungberg (2005) ;Desmet (2015)
Logistics (DFL)	Minimize supply chain costs			1	4	4	B	Y	E	Mather (1992)
Network (DFN)	Minimize supply chain costs	3	3	3	3	4	B	Y	E	Maltzman et al. (2005)
Supply Chain (DFSC)	Minimize supply chain costs		1,5	1,3,5	1,3,5	4	B	Y	E	Lee & Sasser (1995)
Environment (DFE)	Minimize environmental impact	1,2,3,4,5	1,2,3,4	1,2,3,4	1,2,3,4		C	X	E	Fiksel & Wapman (1994), O'Shea (2004)

Classifications: 1= Guidelines, 2= Checklist, 3= Method, 4=Metrics, 5= Math Model
Scope: A= Product, B= System, C= Ecosystem
Character: X= Virtue, Y= Lifecycle
Focus: I= Internal, E= External

According to Holt and Barnes (2010), "character" in this context refers to the framework of reference that a DFX technique requires: whether the development is centered on a certain virtue of the product, or a certain characteristic of the functional system in which it is embedded. In this respect, DFX techniques are divided into two groups: those that optimize the machine with respect to a virtue (cost, quality, etc.), and those that optimize the machine with respect to a lifecycle phase (manufacture, assembly, etc.) (Van Hemel and Keldmann, 1996). These are labeled as DFX_{virtue} and $DFX_{lifephase}$, respectively. Radziwill and Benton (2017) note that DFX_{virtue} techniques do not represent which virtues a machine should have but provide methods to check how well a design satisfies a given virtue. $DFX_{lifephase}$ techniques, meanwhile, help in ensuring that the influence of the whole machine lifecycle phases on the targeted performance is considered. They also explain that the focus is on the degree to which the DFX assimilates the stakeholder's requirements and preferences. Externally-focused DFX methods target supply chain needs, while internally-focused methods target machine specifications, production process requirements, and the type of service.

DFX methods are categorized into five main groups arranged in increasing level of complexity and importance: guidelines, checklists, metrics, mathematical models, and methods (Becker and Wits, 2013). Guidelines provide the guidance and advise required at each design phase. Checklists provide a list of items that need a "Yes"/"No" response and make judgments to verify designs. Metrics may involve both guidelines and checklists but can be presented in quantitative terms. Mathematics models include computational equations and scientific formulas that have been validated. Finally, the methods provide users with the design systematic hierarchy structures and implementation procedures. Table 1 summarizes the clustering and categorization of 36 DFX techniques considered in this paper based on the proposed methodology.

DFX Relative Importance Weight Analysis

The research in this paper is focused on two stages from the machine development lifecycle: the conceptual and detailed design stages listed under the Stuart Pugh: Total Design Activity Model. The reason for selecting this model among the various design methodologies is that it covers the entire lifecycle of machine development. A scientific database of contributions in the field of DFX and machine design is extracted from various repositories such as "Web of Science" and "Science Direct". The assumption is that the greater the number of publications focused on a given DFX technique in the field of machine development phase is, the higher the influence of that technique is. A CiteSpace II software is used to carry out the systematic mapping studies from the scientific database (Chen et al., 2010). It takes the input of the selected publication list and gives the systematic bibliographic analysis of keywords, citations, and publication. In the below-presented method to evaluate the importance weights, the focus is on the number of contributions published during a specific time interval for a given DFX technique. The analysis of the resulting data helps to derive importance weightings of a given DFX technique relative to other techniques published in the same period. For this purpose, the weighted average method is deployed to convert these numbers into weightings and to generate a ranked list. A weight is computed by the frequency of occurrence in a dataset, where the frequency is the number of publications multiplied by the importance weight associated with each period in the dataset from Table 2. The assumption here is that the importance of weight will increase as the period progresses toward the present year. This practice allows for more recent publications to receive more weight relative to older publications. The weighted average of publications is calculated by the following standard equation (1).

$$Weighted\ Average = \frac{Importance\ Weight * Frequency}{\Sigma Frequencies} \quad (1)$$

where P_{DFX} = Frequency of publications related to DFX technique in a specific period; n = Total numbers of DFX techniques; i = Lower year interval; j = Higher year interval

The weighted average of the DFX for a specific time interval is calculated as follows:

$$W_{Pdfx} = \prod_{i}^{j} P_{dfx}\ x\ \text{Importance Weight} \quad (2)$$

The total weighted average of the DFX for a specific time interval is calculated as follows:

$$W_{Pdfx} = \sum_{i}^{j} W_{Pdfx} \quad (3)$$

The percentage relative total weight of a specific DFX with reference to all other DFXs is calculated as follows:

$$W_{Pdfx} = \frac{W_{Pdfx}}{\sum_{i=1}^{n} W_{Pdfx}} \quad (4)$$

Table 2. Importance Weight Associated with Each Period

Importance Weight (0-1)	Papers Period (Years)
0.05	≤ 1995
0.075	1996 ≤ Y ≤ 2000
0.1	2001 ≤ Y ≤ 2005
0.15	2006 ≤ Y ≤ 2010
0.225	2011 ≤ Y ≤ 2015
0.4	Y ≥ 2016

Table 3. DFX Techniques with Their Relative Importance Weight Index

Historical Distribution of the Research Effort of DfX tools								Weighted Average Calculation							
Design For / Time Period	Before 1995	1996-2000	2001-2005	2006-2010	2011-2015	After 2016	Total	Wpdfx≤ 1995 (2)	1995≤Wpdfx ≤2000 (2)	2001≤Wpdfx ≤2005 (2)	2006≤Wpdfx ≤2010 (2)	2011≤Wpdfx ≤2015 (2)	Wpdfx≥ 2016 (2)	Total Weight (3)	% Relative Total Weight (4)
Cost (DFC)	12	7	14	18	23	8	82	0.60	0.53	1.40	2.70	5.18	3.20	13.6	1.7
Manufacturing (DFM)	53	76	119	205	187	113	753	2.65	5.70	11.90	30.75	42.08	45.20	138.3	17.5
Assembly (DFA)	63	77	71	15	11	2	239	3.15	5.78	7.10	2.25	2.48	0.80	21.6	2.7
Manufacturing & Assembly (DFMA)	0	0	0	3	2	3	8	0.00	0.00	0.00	0.45	0.45	1.20	2.1	0.3
Variety (DFV)	0	0	5	16	13	1	35	0.00	0.00	0.50	2.40	2.93	0.40	6.2	0.8
Quality (DFQ)	25	26	21	30	37	12	151	1.25	1.95	2.10	4.50	8.33	4.80	22.9	2.9
Six Sigma (DFSS)	0	6	39	60	68	15	188	0.00	0.45	3.90	9.00	15.30	6.00	34.7	4.4
Quality Manufacturability (DFQM)	1	2	0	0	0	0	3	0.05	0.15	0.00	0.00	0.00	0.00	0.2	0.0
Reusability (DFRE)	0	3	5	1	2	0	11	0.00	0.23	0.50	0.15	0.45	0.00	1.3	0.2
Disassembly (DFDA)	13	37	52	45	48	32	227	0.65	2.78	5.20	6.75	10.80	12.80	39.0	4.9
Reliability (DFR)	47	32	69	123	176	65	512	2.35	2.40	6.90	18.45	39.60	26.00	95.7	12.1
Testability (DFT)	218	261	228	293	264	101	1365	10.90	19.58	22.80	43.95	59.40	40.40	197.0	24.9
Obsolescence (DFO)	0	0	1	0	3	0	4	0.00	0.00	0.10	0.00	0.68	0.00	0.8	0.1
Maintainability (DFMAI)	17	5	5	7	9	10	53	0.85	0.38	0.50	1.05	2.03	4.00	8.8	1.1
Serviceability (DFSE)	1	1	2	3	2	5	14	0.05	0.08	0.20	0.45	0.45	2.00	3.2	0.4
Robustness (DFRO)	1	3	9	8	18	8	47	0.05	0.23	0.90	1.20	4.05	3.20	9.6	1.2
End-Of-Life (DFEL)	0	2	8	7	5	9	31	0.00	0.15	0.80	1.05	1.13	3.60	6.7	0.8
Remanufacture (DFRem)	0	7	3	2	8	1	21	0.00	0.53	0.30	0.30	1.80	0.40	3.3	0.4
Failure Modes (DFMEA)	1	0	0	0	0	0	1	0.05	0.00	0.00	0.00	0.00	0.00	0.1	0.0
Material Substitution (DFMS)	4	0	1	5	10	3	23	0.20	0.00	0.10	0.75	2.25	1.20	4.5	0.6
Modularity (DFMO)	0	1	6	3	4	1	15	0.00	0.08	0.60	0.45	0.90	0.40	2.4	0.3
Affordances (DFAF)	0	0	0	0	3	0	3	0.00	0.00	0.00	0.00	0.68	0.00	0.7	0.1
Empowerment (DFEM)	3	1	1	1	2	0	8	0.15	0.08	0.10	0.15	0.45	0.00	0.9	0.1
Lifecycle (DFLC)	0	2	1	3	2	1	9	0.00	0.15	0.10	0.45	0.45	0.40	1.6	0.2
Transportability (DFTR)	1	2	0	0	0	0	3	0.05	0.15	0.00	0.00	0.00	0.00	0.2	0.0
Mass Customization (DFMC)	0	4	6	11	10	2	33	0.00	0.30	0.60	1.65	2.25	0.80	5.6	0.7
Adaptability (DFAD)	1	0	0	5	7	4	17	0.05	0.00	0.00	0.75	1.58	1.60	4.0	0.5
Lean Six Sigma (DFLSS)	0	0	0	1	2	0	3	0.00	0.00	0.00	0.15	0.45	0.00	0.6	0.1
Sustainability (DFS)	2	6	20	35	104	83	250	0.10	0.45	2.00	5.25	23.40	33.20	64.4	8.1
Recyclability (DFREC)	5	4	5	2	2	1	19	0.25	0.30	0.50	0.30	0.45	0.40	2.2	0.3
Energy Recovery (DFER)	0	0	1	1	0	1	3	0.00	0.00	0.10	0.15	0.00	0.40	0.7	0.1
Logistics (DFL)	1	3	1	3	5	1	14	0.05	0.23	0.10	0.45	1.13	0.40	2.4	0.3
Network (DFN)	3	5	8	16	33	11	76	0.15	0.38	0.80	2.40	7.43	4.40	15.6	2.0
Supply Chain (DFSC)	1	0	2	7	9	5	24	0.05	0.00	0.20	1.05	2.03	2.00	5.3	0.7
Environment (DFE)	26	109	153	112	85	39	524	1.30	8.18	15.30	16.80	19.13	15.60	76.3	9.6

RESULTS AND DISCUSSION

From Table 1 it can be observed that comparably few techniques have been developed over the years for the early machine design stages relative to the later stages. This can be related to the fact that the physical variables of the machine being designed in the present case are still undefined. On the other hand, most of the machine-related DFX techniques are focused on the conceptual and detailed design phases, while system-related techniques concentrate on detailed design. Moreover, ecosystem-related concepts apply to all five design phases. The machine design environmental factor is becoming one of the main requirements in the conceptual and detailed design stages, and, because of environmental considerations, some machines are redesigned. Also, it can be concluded that the detailed methodologies for DFM, DFA, DFQ, and DFV have been proposed, while, for DFS and DFSC, there are only applicable guidelines and mathematical models available. The proposed categorization describes and specify the different structures type in a DFX technique; however, it fails to explicitly express which design activities should be addressed first and which of the techniques nor their implementation order so that they fulfill the machine design intent.

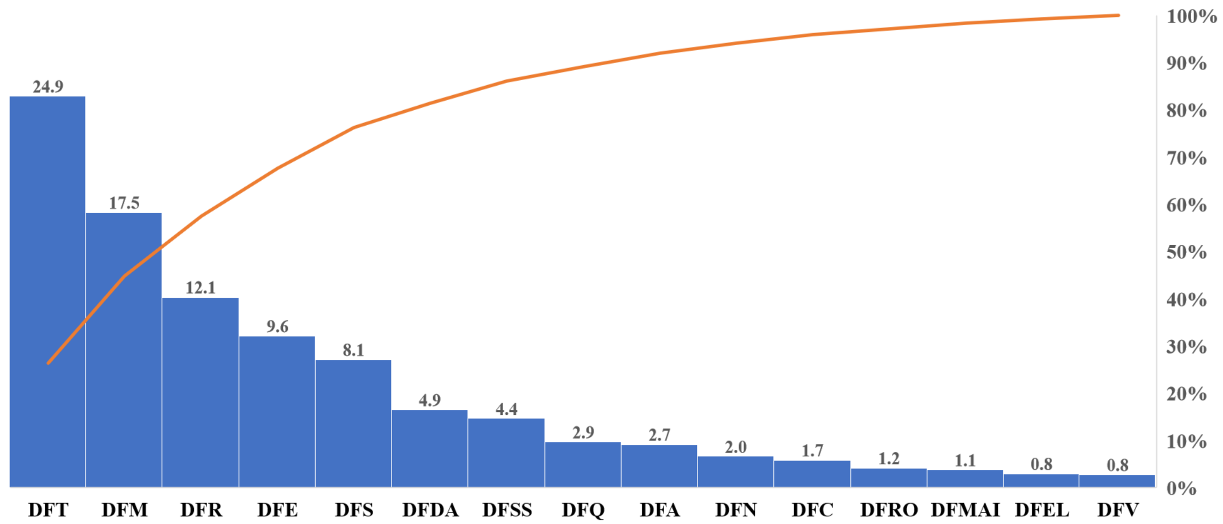

Figure 5. DFXs Relative Importance Weight Distribution Percentage

In this paper, a relative importance weight index is proposed to indicate the amount of effort spent by the researchers on a given DFX technique. In the left pane of Table 3, the number of published papers for each DFX technique in 5-year increments is tabulated. From the resultant table, it can be concluded that the interest rises for Assembly in 1996-2000. Then, Environment emerges as a vital DFX technique for the 2001-2005 interval. After 2005, Testability and Manufacturing garner increasing attention. Furthermore, the focus of research work is found to shift from the product scope to the system and then ecosystem after 1995. Also, a misleading conclusion could be drawn from the matrix if a weighting system is not implemented for the published papers. Figure 5 represents the generated ranked list, where DFT and DFM have recorded higher levels of importance (24.9%, 17.5%) in comparison to DFEL and DFV (0.8%), respectively. Future development efforts should be focused on bridging both scheme normative issues, concerned with the design decision-making theoretical logic, and descriptive issues, concerned with its practicalities together. Also, future research should be directed towards validating the proposed DFX scheme in other engineering domains, to widen and promote the applicability of DFX techniques.

CONCLUSION

This paper summarizes findings based on a comprehensive literature review of various DFX techniques in the broad area of machine development. A clustered collaborative scheme was proposed housing thirty-six DFX techniques, revealing their links and interdependencies across five machine design phases. Moreover, the quantitative research on the maturity of DFXs across the years shows that the combined relative importance percentage allocated with top-ranked 15 DFXs (e.g., DFT, DFM, DFR, DFE, etc.) is 94.7%, which signals an increased level of importance and preparedness of these most effective, efficient, and versatile DFX techniques for machine design development.

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