A Decision Tool to Simulate the Concurrent Interdependencies Between Multi-DFX Techniques in Machine Design Conflict Resolution

A. Itani[a], R. Ahmad[b], and M. Al-Hussein[c]

[a,c] Department of Civil and Environmental Engineering, University of Alberta, Canada
[b]Department of Mechanical Engineering, University of Alberta, Canada
E-mail: aitani@ualberta.ca, rafiq.ahmad@ualberta.ca, malhussein@ualberta.ca

Abstract –

The overall performance of a life-cycle phase under investigation can be improved if Multi-Design for X (MDFX) technique's design guidelines are applied concurrently. However, the complexity of selecting MDFX techniques at the conceptual and detailed design stages during machine development can increase by uncertain and imprecise knowledge about the MDFX interdependencies. For many industrial companies, alleviating the design decision complexity at these stages can have a positive impact on the industry's competitive market. Therefore, it becomes crucial to have a robust MDFX tool embedded with conflict resolution in valuing potential applications to justify their cohesion. Some limitations on the compatibility between MDFX remain a challenge. The unresolved challenge is how the information contained within MDFX can be organized such that the implications of design decisions are proactively evaluated and implemented. To address this challenge, an efficient decision tool for applying MDFX in the conceptual and detailed machine design development phases is proposed. In this paper, the relative importance of DFXs guidelines and the essence of the interactions that arise between them are also studied. Also, a matrix model with multi-layers to simulate the interactions between MDFX is suggested to resolve the conflict of experts' opinion and aggregates the decision criteria layers into a single output. The proposed decision tool was applied in a machine design case study and shows its effectiveness in the decision-making process by eliminating MDFX negative interactions and aiding the designer in shaping the optimal machine design with less development cost and time.

Keywords –

Multi-Design for X (MDFX); life-cycle cost; conceptual and detailed design stage; conflict resolution; multi-layers.

1 Introduction

The implementation of MDFX in concurrent engineering machine design can result in contradictory and conflicting conclusions and recommendations for the designer's design-making process. Several independent studies have started to investigate and analyze these contradicting interactions by using various frameworks developed by Watson that can quantify the MDFX usefulness by design phase [9]. They concluded that MDFX, depending on where they are implemented during the machine development process, have a varying impact threshold. Whereas Willcox and Sheldon realized that the implementation of Design for Assembly methodology is most useful at the conceptual stage [10]. Because the tool component analysis is the main part of the methodology, it is preferred during the machine detailed design stage. The DFA analysis tool is an unreliable tool to be utilized during the conceptual machine stage because the design details required to undergo the analysis are not available at this stage. Hence, if the analysis tool is not effective at the conceptual design stage, then the alternative will be the benefits that the design guidelines of a specific DFX provide. So, to minimize the machine redesign possibilities and reduce the cost/time of this activity, the analysis tool should consider the importance of DFX guidelines.

Some research was undertaken to investigate how to tackle the conflicting implementation guidelines of MDFX. Thurston suggests a methodology to model the design decision results on the interval of a machine life-cycle [8]. A framework was developed to facilitate the decision-making process through ranking the design alternatives and calculating design trade-offs. In engineering design, it is a powerful analysis tool for decision making where multiple criteria and objectives exist. Unfortunately, for most applications, this method is very complicated and extensively time-consuming for designers in small to medium-sized organizations. If this ranking method is adopted to classify the design guidelines, it would be unnecessarily tedious because the model used by Thurston is to some extent more complicated to implement than what is required for this application. A simpler and faster method for trade-off analysis between MDFX is to implement a matrix approach. Meerkamm concludes that if MDFX techniques are to be utilized in a problem context, then their design guidelines will often contradict and constrain the design output [4]. Consequently, as explained by Watson et al., finding an optimal solution is becoming a difficult task for designers [9]. As the design guidelines tend to be the DFX toolbox's most flexible aspect, they accurately indicate the nature of the DFX interactions and links between them and their concurrent interdependencies in ultimately finding an optimal design solution.

It is important to evaluate the application of MDFX in machine design development comprehensively. But due to the absence of information in the conceptual machine stage, problems and conflicts can arise when MDFX techniques are employed. This is because of a lack of information and vague objectives, which interfere with the designer's ability to evaluate design decision alternatives precisely. Decisions that emerge from applying one DFX technique seem to be good for one phase of the machine life cycle but can conflict with other life cycle phases. The designer should oversee the concurrent effects of the decision-making process in machine design. If the previous decisions are based on inaccurate information, the following design stages will be affected significantly. The application of MDFX techniques in machine design development requires effective decision support systems. In view of this, a decision support tool that simulates the concurrent interdependencies between MDFX techniques during the conceptual machine design stage is proposed in this paper.

2 Methodology

The methodology presented in this section is based on Watson et al.'s model that uses a weighted matrix method to exploit the interactions between MDFX [9]. The matrix method is extended to simulate the concurrent interdependencies between MDFX. The model output provides three useful indices. The first one indicates major areas of potential conflict occurring between the compared MDFX. The second illustrates how the value of a specific guideline is modified when interacting with the competing DFX guidelines. And the third is measuring the DFX techniques in terms of time metrics to estimate and reliably verify DFX interactions and design decisions comprehensively.

2.1 Procedure of the matrix

The methodology for assessing and ranking the DFX's competing design guidelines requires six distinct tasks to be undertaken. These tasks are described in the flowchart presented in Figure 1.

2.2 Task 1: Determine DFX overall weight using the analytical hierarchy process (AHP) method

The first task involves selecting and calculating the overall relative importance (weight) of the chosen DFX techniques. This can be achieved by calculating the weight of each DFX technique separately with respect to the design criteria, and then by combining them in an AHP model developed by Saaty to determine their relative importance in machine conceptual and detailed design stages [6]. In general, the relative importance of a DFX technique varies as to where and when it can be applied during the machine development process [1]. He concludes that the area where a DFX technique can be utilized is defined by company and customer requirements, production capabilities, and industry orientations, in addition to other considerations.

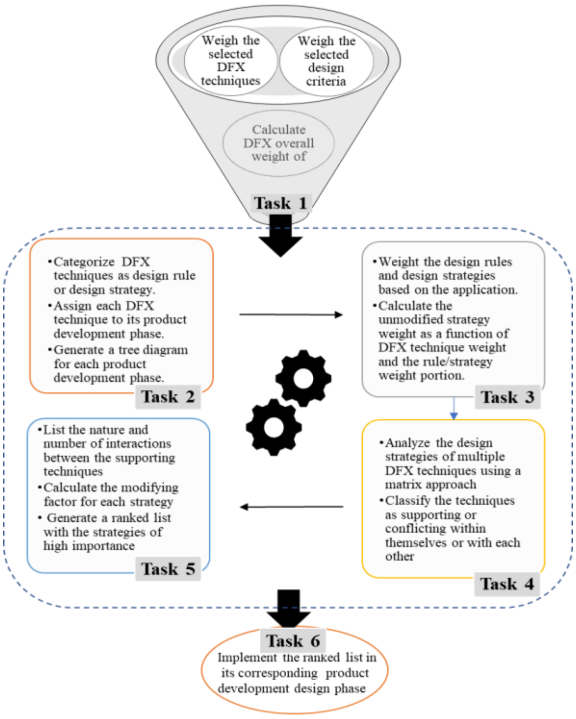


Figure 1. Multi-DFX techniques matrix model flow chart

The product design specification (PDS) must be formulated at the beginning of the project based on the statement of needs prior to any design activity, as shown in Figure 2. Thus, it acts as the governor for the total design activity model, because it revolves around the boundaries of each design stage for any machine.

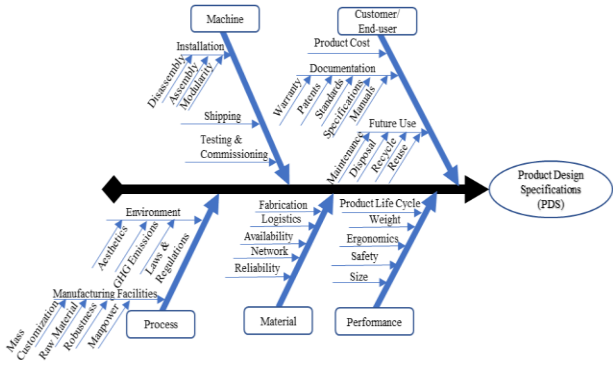


Figure 2. Product design specification (PDS).

The PDS forms a progressive, evolutionary, and extensive written document that evolves in consideration of the final machine characteristics. The PDS is then translated into design criteria that are followed by the design team, and as such, each design criterion will be associated with one or multiple DFX techniques that can satisfy its requirements. By adapting the total life-cycle cost/time method developed by Lukasz and Tomasz, the design team can successfully estimate each DFX technique's effect with respect to the other, and those values will be an indicator as to how much each DFX can reduce the development life-cycle overall cost and time [2].

DFX techniques are weighted with respect to each design criterion to generate an overall general normalized importance weight W_{DFXG} with a total value of 1. From that, the time required for each design activity T_{DFXG} can be derived under a certain DFX. This weighting factor will then be adopted in the general model for conceptual and detailed design stages. The weighting in the AHP model must rely on the designer's experience and intuition. W_{DFXG} and T_{DFXG} are calculated using Equation (1) and (2), respectively, as follows:

$$W_{DFXG} = \frac{Cost\ x}{Cost\ T} \qquad (1)$$

Where,

$Cost_x$= The cost of life-cycle area x

$Cost_T$= The combined cost of the life-cycle

$$T_{DFXG} = W_{DFXG}\ x\ T_t \qquad (2)$$

Where,

T_{DFXG}= The allocated time for a specific DFX in days

T_t= The total time for the design activity in days

2.3 Task 2: Generate tree diagram to classify DFX design guidelines

In this section, the machine development process is categorized, and the hierarchical level of the DFX technique design guidelines is established. Watson, Radcliffe et al. proved that if DFX decision analysis tools are utilized during conceptual and detailed machine design stages, they could improve the design performance significantly [9]. They also concluded that most DFX techniques fail to give what is expected because they merely provide the designer with directions on how and when the design rules can be implemented.

Pugh's Total Design Activity Model is used to describe the machine development process [5]. The model phases are 1) user need; 2) machine specification; 3) conceptual design; 4) detail design; 5) manufacture; and 6) and sales. Though design activities might not always have to occur concurrently in the sequence outline by Pugh, his machine development model provides a detailed structured procedure of all the stages required. Table 1 contains some design guidelines examples which are the most applicable for machine design development process extracted from the Design for Assembly (DFA) methodology [2].

Table 1. DFA guidelines per design stage

Specification	• Standardize a machine's style. • Establish the machine design specification.
Concept Design	• Reduce the number of parts and components. • Eliminate machine features that do not have any tangible value to the customer. • Standardize a machine's style. • Using new materials and technologies. • Rational machine design by modules and product families.
Detailed Design	• Design multi-functional parts. • Developing the machine features that facilitate the positioning. • Avoid costly clamping systems.
Manufacture	• Simplicity. • Adapted tolerances. • Consideration of process-related design guidelines.

The second task in constructing the model is to organize the DFX technique design guidelines into a decision tree using a hierarchical structure. Each DFX technique consists of primary and secondary design guidelines called design rules and design strategies, respectively. The tree diagram consists of three levels where the first level is associated with the general DFX tool under study, the second level is associated with

DFX design rules, and the third level is associated with DFX design strategies. Table 2 contains an example of the hierarchical tree using the DFA guidelines during the detailed design phase [2].

Table 2. DFA detailed design stage guidelines

Design Rules	Design Strategies
Reduce the number of parts and their types	Reduce unstandardized fasteners. Eliminate parts that function as connectors and conduits. Design multi-function parts. Do not follow piece-part producibility guidelines.
Eliminate physical adjustments	Reduce the number of physical parts between the machine input and output functions. Relocate critically related part surfaces close together. Implement kinematic design procedures and principles.
Ensure adequate clearance and unrestricted vision	Ensure adequate clearance for hands, tools, and subsequent process. Ensure that the vision of the operation is not restricted or compromised.
Minimize re-orientations	Minimize the necessity for reorientations during and after parts installation.

2.4 Task 3: Determining the weightings levels of the guidelines

The third task requires that the DFX technique design rules and strategies be weighted. Regarding the weighting levels, they are determined in each phase, which gives the designer a general design overview of the machine development process. The design rules weighting, W_{TR}, is determined independently, regardless of the design strategies number (on a scale of 1 to 10). While the design strategies weighting, W_{PS}, is determined in proportion to the design rule it corresponds to on a scale of 1 to 10, such that the total weight summation under design rules is equal to 1. The total weight of each design strategy, W_{TS}, is calculated using Equation (3) by multiplying the DFX technique overall weight, the design rule total weight, and the design strategy proportional weight. Thus, the total weight of each design strategy can fluctuate between 0 and 1. While the time required for each design strategy, T_{TS}, is calculated in days using Equation (4) by multiplying the strategy calculated weight from Equation (3) by the allocated time for the selected DFX divided by the summation of strategies weight for the selected design phase.

$$W_{TS} = W_{DFXG} \text{ x } W_{TR} \text{ x } W_{PS} \qquad (3)$$

$$T_{TS} = \frac{T_{DFXG}\ x\ W_{TS}}{\sum_{i=0}^{n} W_{TS}} \quad i=0,1,2\ldots.\ n \qquad (4)$$

2.5 Task 4: Identifying interactions and links between guidelines

The fourth task involves determining the interactions and links between the strategies and reporting them inside the matrix model. The severity of any conflicts can be measured from these interactions. The matrix model can be utilized to compare multiple numbers of strategies from MDFX techniques. However, the process of finding each relationship between strategies can become tedious and time consuming for MDFX guidelines. It is assumed that not more than four DFX tools and a maximum number of ten strategies per phase should be adopted in the model.

Table 3. Strategies comparison values

R Values	Description
+ 1	Two or more strategies interact positively.
+0.5	One strategy supports positively the other in a broader scope.
0	No interaction occurs between the design strategies.
-0.5	One strategy supports negatively the other in a broader scope.
-1	Two or more strategies interact negatively.

From the matrix model, it is possible to pinpoint any conflict between two strategies to alert the designer that special consideration should be in place when dealing with them. This is done using the conflict index, CI, which quantifies the severity of the conflict. When a negative interaction occurs, the equation to calculate the conflict index is employed. The conflict index constant is calculated using Equation (5) as follows:

$$CI = W_{TS} \text{ x } W_{TS'} \text{ x } R \qquad (5)$$

if CI < -10 then conflict must be examined.

Where,
$W_{TS'}$ = Total weight of compared strategy
R = The comparison value for the two design strategies, as shown in Table 3.

2.6 Task 5 & 6: Generating the ranked list of DFX strategies

The fifth task involves calculating the overall value ($\square_{TS}$) of a design strategy considering strategies weight and their interactions with each other. The main process is based on the assumption that each design strategy has a total weighted value (W_{TS}) and interactions with other strategies adjust this. The prime factor is a function of the comparison index and the compared guideline weight. By summing the prime value over all the DFX interactions, a global scaler is determined. Equations (6) & (7) calculate the overall value ($\square_{TS}$) as follows:

$$\square_{TS} = W_{TS}\,(1 + \delta\ \square) \qquad (6)$$

$$\square_{TS} = W_{TS}\,\left(1 + \sum \frac{(W_{TS'}\ x\ R\ x\ S\ )}{100}\ \right) \qquad (7)$$

Where,

$$S=\frac{15}{W_{TS}} \qquad \text{if } W_{TS'}>W_{TS} \text{ and } R<0 \qquad (8)$$
$$S=1 \qquad \text{else}$$

Where,
δ □ =the total prime factor overall strategies and DFX techniques
S = the scaler
15 = Number of DFX techniques being researched
100 =scaling factor

In Equation (8), the scaler considers the instances when a low weight design strategy conflicts with a high weight one. Having determined the total strategy value, a ranked list can be configured to be implemented in the machine development. Any design strategies that have a negative total value should be ignored because if adopted, then it may lead to a life-cycle performance reduction due to its conflicting correlations with other strategies. After generating the ranked list, the redundant design strategies within the competing DFX will be removed to save time and to eliminate design repetition. However, if both design strategies match each other in the core objective, then the lesser time duration will be selected.

3 Validation Case Study

In this section, the focus of the case study will revolve around a part of the multi-function bridge machine prototype which is the nailing carriage in its conceptual design stage, as shown in Figures 3 and 4.

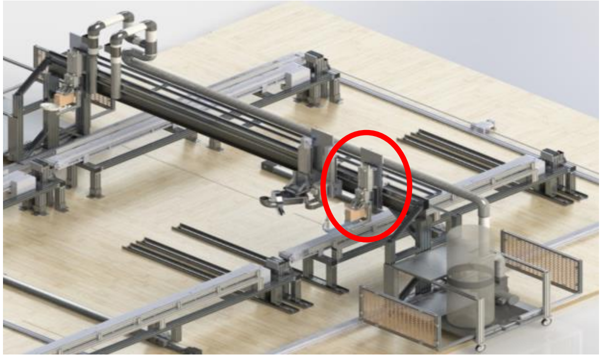
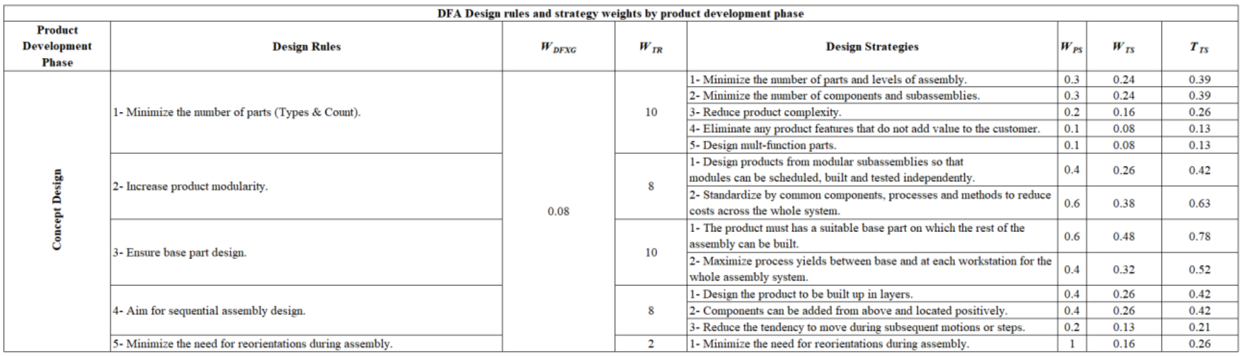


Figure 3. 3D model of multi-function bridge prototype

As the carriage at this stage is primarily a research tool, it is assumed that there would be a maximum amount of flexibility and testability within the variability of the experimental parameters. It also meant that a simple and unique machine would be designed. As the carriage will be operating in a large area with extreme precision at a controlled speed, it is apparent that the geometry and versatility of the carriage are considered as a major design criterion. It is also apparent that because the vertical force loads are so small, any part stresses would be negligible.

Figure 4. Nailer carriage detailed view

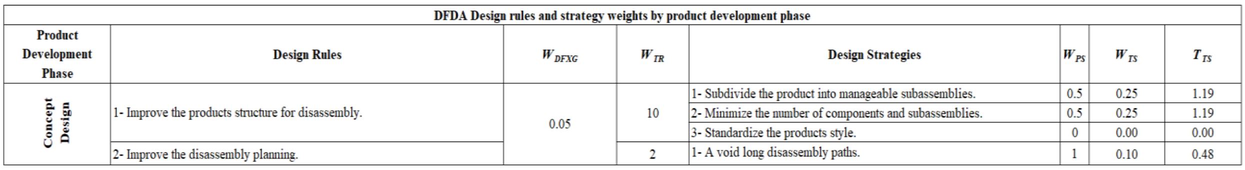
From the PDS, the carriage to be designed is to accommodate multiple configurations of interchangeable tools, such as a nailer, stapler, and screwdriver. This operational requirement results in the device being partially disassembled and re-assembled after each operation and for different sheathing configurations. Regarding parts service life, it is expected that no major parts should fail throughout the device's life. The final requirement is that the device is to be designed and manufactured within a very limited budget. The detailed technical information of the machine development is excluded from this paper for patentability and commerciality of the machine. Instead, some of the case study design related issues are discussed in broad terms. The timeline to complete the carriage conceptual design was 60 calendar days. These days are distributed on all 15 DFX techniques in accordance with their global weighting results.



DFA Design rules and strategy weights by product development phase

Product Development Phase	Design Rules	W_{DFXG}	W_{TR}	Design Strategies	W_{PS}	W_{TS}	T_{TS}
Concept Design	1- Minimize the number of parts (Types & Count).	0.08	10	1- Minimize the number of parts and levels of assembly.	0.3	0.24	0.39
				2- Minimize the number of components and subassemblies.	0.3	0.24	0.39
				3- Reduce product complexity.	0.2	0.16	0.26
				4- Eliminate any product features that do not add value to the customer.	0.1	0.08	0.13
				5- Design mult-function parts.	0.1	0.08	0.13
	2- Increase product modularity.		8	1- Design products from modular subassemblies so that modules can be scheduled, built and tested independently.	0.4	0.26	0.42
				2- Standardize by common components, processes and methods to reduce costs across the whole system.	0.6	0.38	0.63
	3- Ensure base part design.		10	1- The product must has a suitable base part on which the rest of the assembly can be built.	0.6	0.48	0.78
				2- Maximize process yields between base and at each workstation for the whole assembly system.	0.4	0.32	0.52
	4- Aim for sequential assembly design.		8	1- Design the product to be built up in layers.	0.4	0.26	0.42
				2- Components can be added from above and located positively.	0.4	0.26	0.42
				3- Reduce the tendency to move during subsequent motions or steps.	0.2	0.13	0.21
	5- Minimize the need for reorientations during assembly.		2	1- Minimize the need for reorientations during assembly.	1	0.16	0.26

Figure 5. Design for assembly design rules and strategies for the conceptual stage



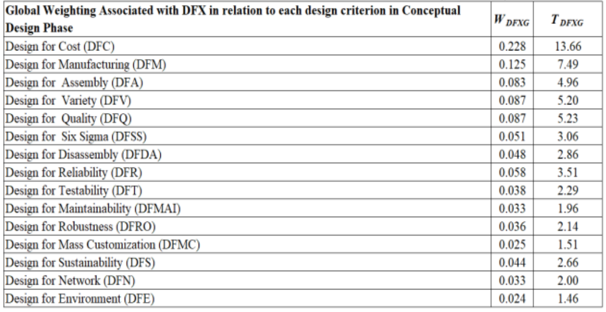
DFDA Design rules and strategy weights by product development phase

Product Development Phase	Design Rules	W_{DFXG}	W_{TR}	Design Strategies	W_{PS}	W_{TS}	T_{TS}
Concept Design	1- Improve the products structure for disassembly.	0.05	10	1- Subdivide the product into manageable subassemblies.	0.5	0.25	1.19
				2- Minimize the number of components and subassemblies.	0.5	0.25	1.19
				3- Standardize the products style.	0	0.00	0.00
	2- Improve the disassembly planning.		2	1- A void long disassembly paths.	1	0.10	0.48

Figure 6. Design for disassembly design rules and strategies for the conceptual stage.

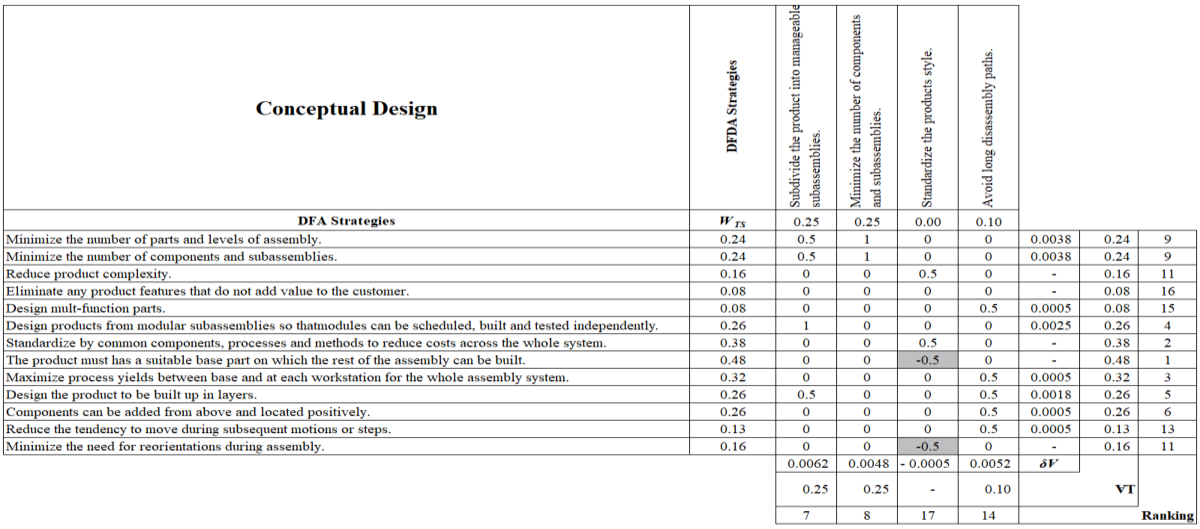
This to allocate time for each DFX technique and to study the effect of utilizing the proposed methodology in the time management of design activities.

Table 4. DFX global weighting results with their time allocations in the conceptual design stage



Global Weighting Associated with DFX in relation to each design criterion in Conceptual Design Phase	W_{DFXG}	T_{DFXG}
Design for Cost (DFC)	0.228	13.66
Design for Manufacturing (DFM)	0.125	7.49
Design for Assembly (DFA)	0.083	4.96
Design for Variety (DFV)	0.087	5.20
Design for Quality (DFQ)	0.087	5.23
Design for Six Sigma (DFSS)	0.051	3.06
Design for Disassembly (DFDA)	0.048	2.86
Design for Reliability (DFR)	0.058	3.51
Design for Testability (DFT)	0.038	2.29
Design for Maintainability (DFMAI)	0.033	1.96
Design for Robustness (DFRO)	0.036	2.14
Design for Mass Customization (DFMC)	0.025	1.51
Design for Sustainability (DFS)	0.044	2.66
Design for Network (DFN)	0.033	2.00
Design for Environment (DFE)	0.024	1.46

In this case, 15 DFX techniques fall under the scope of the conceptual design stage with their global weighting associated with the PDS that was calculated by adopting the AHP model. Table 4 summarizes the results where the total summation of all DFX weighting is equal to 1 and where each DFX has a time allocation associated with it. In this paper, two DFX techniques were selected from the list to demonstrate the model functionality: Design for Assembly (DFA) and Design for Disassembly (DFDA). The DFA technique selected was developed by Boothroyd and Dewhurst [2]. The methodology has been refined and upgraded to provide a realistic and reliable design analysis tool with set of guidelines that are presented in a structured format. The tool follows the same basic procedures to analyze for manual, automatic and robotic assembly with different input data tables for the various processes. For this project, the manual assembly method is adequate. The designed machine would encounter assembly and re-assembly process on a regular basis. This process has a substantial effect on how the design guidelines are interpreted and rated. A team of researchers developed the DFDA technique adopted in this case study at the Manchester Metropolitan University ([7], [11]). The developed technique purpose is focused on the disassembling process to facilitate reconfiguration. Figures 5 and 6 contains the list of design rules and strategies for conceptual design machine development phases for both DFA and DFD techniques. Since two DFX techniques are being investigated, only one decision matrix for the conceptual machine development phase is selected for the demonstration of the comparison and ranking process. Figure 7 shows the conceptual design comparison matrix for DFA versus DFDA highlighting the guidelines interactions.



Conceptual Design	DFDA Strategies	Subdivide the product into manageable subassemblies.	Minimize the number of components and subassemblies.	Standardize the products style.	Avoid long disassembly paths.			
DFA Strategies	W_{TS}	0.25	0.25	0.00	0.10			
Minimize the number of parts and levels of assembly.	0.24	0.5	1	0	0	0.0038	0.24	9
Minimize the number of components and subassemblies.	0.24	0.5	1	0	0	0.0038	0.24	9
Reduce product complexity.	0.16	0	0	0.5	0	-	0.16	11
Eliminate any product features that do not add value to the customer.	0.08	0	0	0	0	-	0.08	16
Design mult-function parts.	0.08	0	0	0	0.5	0.0005	0.08	15
Design products from modular subassemblies so thatmodules can be scheduled, built and tested independently.	0.26	1	0	0	0	0.0025	0.26	4
Standardize by common components, processes and methods to reduce costs across the whole system.	0.38	0	0	0.5	0	-	0.38	2
The product must has a suitable base part on which the rest of the assembly can be built.	0.48	0	0	-0.5	0	-	0.48	1
Maximize process yields between base and at each workstation for the whole assembly system.	0.32	0	0	0	0.5	0.0005	0.32	3
Design the product to be built up in layers.	0.26	0.5	0	0	0.5	0.0018	0.26	5
Components can be added from above and located positively.	0.26	0	0	0	0.5	0.0005	0.26	6
Reduce the tendency to move during subsequent motions or steps.	0.13	0	0	0	0.5	0.0005	0.13	13
Minimize the need for reorientations during assembly.	0.16	0	0	-0.5	0	-	0.16	11
		0.0062	0.0048	- 0.0005	0.0052	δV		
		0.25	0.25	-	0.10		**VT**	
		7	8	17	14			**Ranking**

Figure 7. DFA vs DFDA comparison matrix.

4 Results and Discussion

As highlighted in the matrix shown above in Figure 7, two design strategies have conflicted, so special consideration must be in place to resolve this conflict before they the ranking procedure starts. However, the conflict occurs, in this case, is when the designer simultaneously attempts to minimize the need for reorientation during assembly while attempting to standardize the machine during disassembly. It is assumed that the arising conflict could be ignored, subject to further investigation, as the conflict index slightly exceeds the threshold value of ten.

Figure 8 summarizes the ranking of the strategies in descending order based on their respective total value. After analyzing the results, the designer can eliminate from the ranked list the strategies that are repeated or have the same core objective, while the strategies with the same ranking order can be implemented concurrently in the design process to emphasize their relatively equal importance.

Figure 9 summarizes the modifications after the designer has conducted the analysis. If both selected DFX techniques were to be applied in standalone mode, then after several design iterations they will conflict, which would lead to a machine redesign. The redesign process is a costly and time-consuming activity, and by applying this methodology, the designer can avoid the pitfall of such activity.

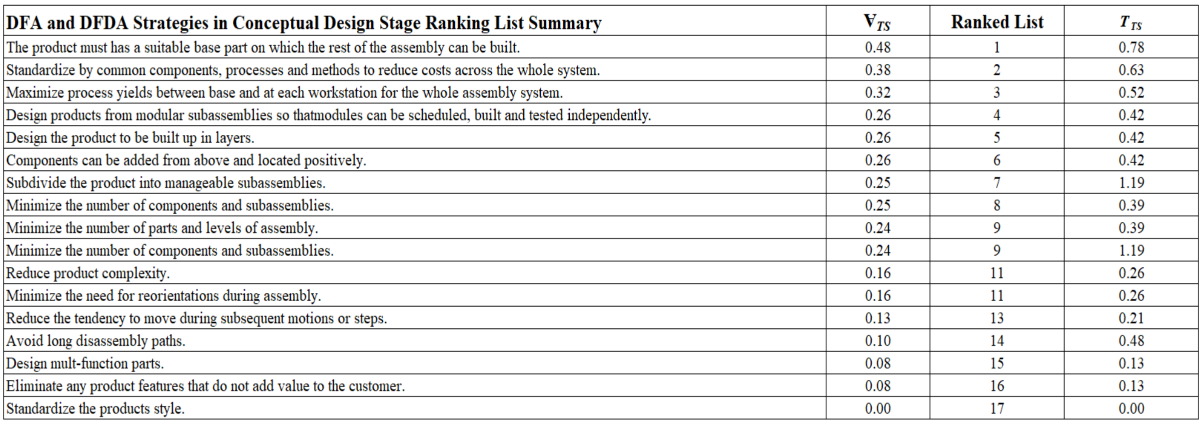
If the designer is to apply DFA with 4.96 days and DFDA with 2.86 days independently then the total time required for both will be 7.82 days. However, if they are applied together, the redundant design strategies between the two and the conflicted area will be removed and adjusted before initiating the design activity. Thus, reducing the total time to 6.63 days with a difference of 1.19 days.

Some observations were concluded after applying the matrix model in the case study mentioned above such as if the value of the conflict index constant exceeds a value of negative ten, then it can be declared that a conflict of substantial consequences has occurred, and some considerations are required to resolve it. This conflict can be resolved and avoided by implementing some tactics as follows:

1. If the conflict index constant is close to ten, then the resulted conflict could be ignored and eliminated on the basis that it will create a down weight effect on the other design strategies in the ranked list.
2. Develop and integrate a design methodology after examining the conflict-specific details to decrease the negative interaction areas between strategies—this is very useful in areas where partial conflict has been spotted (CI ≤ -10).
3. The matrix model ranking function will eliminate any two design strategies that have a large total value difference, and it will eliminate negative values too.

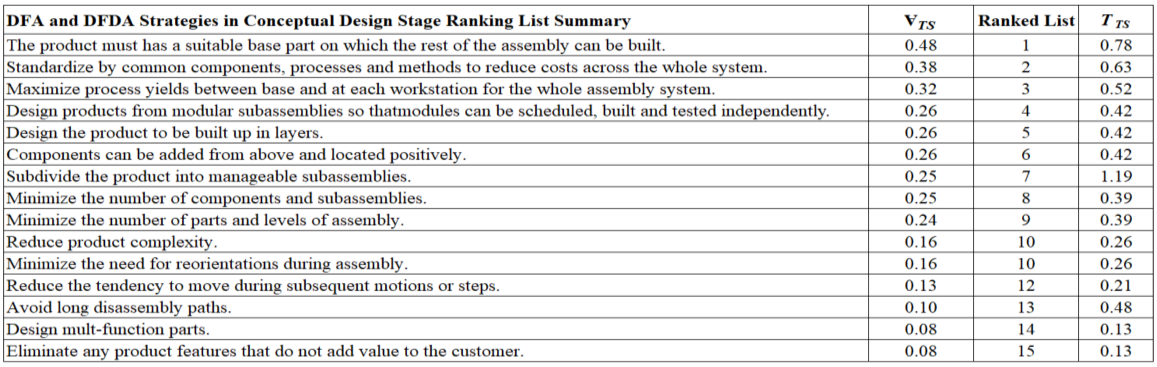
The weighting procedure of any parameter may sometimes be a subjective process, as two different designers may weigh the same guideline differently. This difference comes from the usage circumstances, the experience, and interpretation of the designers as to what the guideline means. However, these differences will not give the user a misleading result because the guidelines are interpreted according to the designer's understanding.

That said, future work will be required to extend the applicability of the decision tool in the DFX trade-off analysis with respect to cost and quality to provide a better understanding of client needs while controlling the machine lifecycle. Moreover, the future development of this methodology will be required to cover the other phases of the machine lifecycle (e.g., embodiment design, manufacturing, and sales).



DFA and DFDA Strategies in Conceptual Design Stage Ranking List Summary	V_{TS}	**Ranked List**	T_{TS}
The product must has a suitable base part on which the rest of the assembly can be built.	0.48	1	0.78
Standardize by common components, processes and methods to reduce costs across the whole system.	0.38	2	0.63
Maximize process yields between base and at each workstation for the whole assembly system.	0.32	3	0.52
Design products from modular subassemblies so thatmodules can be scheduled, built and tested independently.	0.26	4	0.42
Design the product to be built up in layers.	0.26	5	0.42
Components can be added from above and located positively.	0.26	6	0.42
Subdivide the product into manageable subassemblies.	0.25	7	1.19
Minimize the number of components and subassemblies.	0.25	8	0.39
Minimize the number of parts and levels of assembly.	0.24	9	0.39
Minimize the number of components and subassemblies.	0.24	9	1.19
Reduce product complexity.	0.16	11	0.26
Minimize the need for reorientations during assembly.	0.16	11	0.26
Reduce the tendency to move during subsequent motions or steps.	0.13	13	0.21
Avoid long disassembly paths.	0.10	14	0.48
Design mult-function parts.	0.08	15	0.13
Eliminate any product features that do not add value to the customer.	0.08	16	0.13
Standardize the products style.	0.00	17	0.00

Figure 8. DFA vs DFDA strategies ranking list in the conceptual design stage (before analyzing).



DFA and DFDA Strategies in Conceptual Design Stage Ranking List Summary	V_{TS}	**Ranked List**	T_{TS}
The product must has a suitable base part on which the rest of the assembly can be built.	0.48	1	0.78
Standardize by common components, processes and methods to reduce costs across the whole system.	0.38	2	0.63
Maximize process yields between base and at each workstation for the whole assembly system.	0.32	3	0.52
Design products from modular subassemblies so thatmodules can be scheduled, built and tested independently.	0.26	4	0.42
Design the product to be built up in layers.	0.26	5	0.42
Components can be added from above and located positively.	0.26	6	0.42
Subdivide the product into manageable subassemblies.	0.25	7	1.19
Minimize the number of components and subassemblies.	0.25	8	0.39
Minimize the number of parts and levels of assembly.	0.24	9	0.39
Reduce product complexity.	0.16	10	0.26
Minimize the need for reorientations during assembly.	0.16	10	0.26
Reduce the tendency to move during subsequent motions or steps.	0.13	12	0.21
Avoid long disassembly paths.	0.10	13	0.48
Design mult-function parts.	0.08	14	0.13
Eliminate any product features that do not add value to the customer.	0.08	15	0.13

Figure 9. DFA vs DFDA strategies ranking list in the conceptual design stage (after analyzing).

5 CONCLUSION

Engineering design is an iterative process of solution generation and evaluation. It requires a designer to take a forward-thinking and a look ahead approach when finalizing a solution. In a dynamic environment, a concurrent application of MDFX techniques during the design process can be organized into multiple stages in which both evaluation and decision are needed. The main theme of this paper was to present the need for a tool that can reliably estimate and verify the time/benefits of applying MDFX in a harmonized way in machine design. As a result, a decision support tool that can aid the designer in the decision-making process when MDFX are utilized will be required. The main feature of a design decision simulation tool is to enable designers to foresee and explore lifecycle consequences during the machine design. Also, to provide a structured workflow specifying how and when MDFX techniques can be applied with the ability to quantify the arising conflict that may occur between them. The tool's fundamental core is based on the information contained within the DFX guidelines, which may be classified as either a design strategy or rule so their interactions can be examined explicitly. Thus, the generation of a ranked list can be integrated in a time-effective and strategic manner, thereby shrinking the machine design time by at least 15%. As demonstrated, the MDFX decision tool can be implemented to serve as a generative decision system that proactively aids the designer in the decision-making process.

6 ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC).

7 REFERENCES

[1] Ahmad, R., Lahonde, N., and Omhover, J. F. (2014). “Game Methodology for Design Methods and Tools Selection.” *Journal of Learning Design*, 7(1), 1-9.

[2] Boothroyd, G. and Dewhurst, P. (1989). “Product Design for Assembly.” *Boothroyd Dewhurst Inc.* Wakefield, USA.

[3] Lukasz, M. and Tomasz, N. (2007). “Dfx Platform-a Holistic Approach to Design Concepts Evaluation.” Guidelines for a Decision Support Method Adapted to NPD Processes, 21-22.

[4] Meerkamm, H. (1994). “Design for X - A Core Area of Design Methodology.” *Journal of Engineering Design*, S (2), 145-163.

[5] Pugh, S. (1991). “Total design: Integrated methods for successful product engineering.”

[6] Saaty, T. L. (2008). “Decision making with the analytic hierarchy process.*” International journal of services sciences*, 1(1), 83-98.

[7] Simon, M., Fogg, B., and Chambellant, F. (1992). “Design for Cost-Effective Disassembly.” *Technical Report* DDRnRl.

[8] Thurston, D. (1991). “A Formal Method for Subjective Design Evaluation with Multiple Attributes.” *Research in Engineering Design*, 3 (2), 105-122.

[9] Watson, B., Radcliffe, D., & Dale, P. (1996). “A meta-methodology for the application of DFX design guidelines.” *In Design for X* (pp. 441-462). Springer, Dordrecht.

[10] WILCOX, M., and Sheldon, D. (1993). “How the design team in management terms will handle the DFX tools.” *In Proceedings of the 9th International Conference on Engineering Design* (pp. 875-881).

[11] Zhang, 'B., Simon, M., and Dowie, T. (1993). “Initial Investigation of Design Guidelines and Assessment of Design for Disassembly.” *Technical Report*, DDRTR03, Aug (pp. 17-19).