A DSM Approach to Modularize for Reusability

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Abstract: Over the past years there has been an increasing interest in the incorporation of modularity for the goal of reuse. Modularization can promote reusability by creating groups of components, a module, that as a whole can be reused in second generation systems. This study presents an approach to generate practical clusters of components based on similarities in modularity driver values while taking in account component dependencies and component-to-component constraints. The modularity driver values and constraints are used as an extra input for the Design Structure Matrix tool, enabling designers to base modularization choices on the DSM clustering. This results in an approach to modularize systems for reusability.

Keywords: Modularization, Design for Reusability, Design Structure Matrix, Modularity drivers

1 Introduction

Over the last decade, an increasing concern regarding the environmental impact of the industrial industry has encouraged manufacturers to reconsider their product design processes from the view of sustainability. The integration of modularity in product design for the purpose of sustainability has gained significant interest from both academia and industry.

The incorporation of modular design principles enables the creation of products and systems with higher levels of reusability. Modular design, or modularization, can promote reusability by creating groups of components, a module, that as a whole can be reused in second generation systems. Unlike recycling, which consists of reprocessing wastes to produce new materials, reuse preserves the function of the reused material or component after its reconditioning (Iacovidou and Purnell, 2016; Brutting et al., 2018). Reuse is the employment of components and modules obtained from end of-life products as spare parts or in the new product (Lambert and Gupta, 2005). Multiple studies have been carried out aimed at formalizing the search for modules (Lee and Shin, 1990; Lambert and Gupta, 2005; Mascle, 1995; O'Shea et al., 2000; Go and S, 1999). However, design for reusability has not been considered the driver of the modularization.

There is much research dealing with modularity and circular economy, but the integration between both is little addressed and needs further practical and theoretical investigations (Machado and Morioka, 2021). In previous literature analytical methods for design for reusability were often rather complicated, and there is a need for practical, simple guidelines (Huang et al., 2012). Few articles focus on exploring the relationships between components, or the modularity and disassembly pattern (Huang et al., 2012). An article by Kimura et al. (2001) elaborates on the lacking investigation into modularization for parts reuse. The need for further exploration of integration of modularity and reusability is the driver of this research.

The successful implementation of modularization requires an approach that allows designers to effectively organize and manage the relationships among different components and modules within a system. This research investigates a methodology that incorporates Design Structure Matrices (DSMs) when designing for reusability through modularization. This research specifically comprises; an exploration of the methodology to incorporate the use of Design Structure Matrices when Designing for Reusability, using the approach of modularization.

1.1 Related work

Reuse, in this study, is defined in the sense of reusing components of a system in similar systems. Reuse avoids sourcing raw materials and requires little energy for reprocessing (Brutting et al., 2018). Product reuse is often viewed as an effective strategy for enhancing environmental sustainability given the potential environmental advantage of reuse over new production (Verter et al., 2023). In order to increase the possibility of reuse after product usage, it is useful to identify appropriate product modularization (Kimura et al., 2001).

Product modularization can be defined in different ways. Multiple different modularity metrics have been reviewed (Hölttä-Otto et al., 2012). It is concluded that there is no generic way of defining and quantifying modularity. Modularity in this study comprises the coupling of system components that share dependencies among each other and similarities in modularity driver values. Within design for reusability, each module is considered unit of reuse (Kimura et al., 2001).

The findings of Ma and Kremer (2016) reveal that from an industry perspective modularity has a positive impact on sustainability. A study by Sonego et al. (2018) explores the intersection between modularity and sustainable design from the perspective of the product life cycle. They conducted a systematic review of the literature to explore the intersection between modularity and sustainable design. Schischke et al. (2019) discussed several modularity approaches related to circular design strategies such as, material modularity, internal modularity for serviceability, repair modularity, platform modularity, do-it-yourself repair modularity, upgrade modularity, mix and match modularity, add-on modularity, re-purposing and system modularity. Yan and Feng (2014) propose a methodology of sustainable design oriented product modularity to integrate sustainable factors such as environment, economy, and society into product design process through the product representation with respect to module clustering criteria. Kimura et al. (2001) perform a commonality analysis to identify the modules shared by different product in order to proposes a modular design method for achieving component recycling. Not all modularity approaches can be utilized in all systems nor are specifically useful in the scope of design for reusability. This research will explore a method for modularization that can be utilized in the reusability scope.

2 Methods

The main tool used in this study is the Design Structure Matrix (DSM). The tool allows for a structured analysis of interactions between components of a system making it a valuable tool for analyzing and optimizing a design (Eppinger and Browning, 2012). Furthermore, the DSM is a compact and scalable approach to represent product architecture, making it suitable as a practical design tool (Williamsson et al., 2018). The clustering of components in the DSM by reordering the rows and columns can provide new insights into system decomposition and integration (Browning, 2001). Furthermore, DSMs can promote modular product design by providing useful insights into the dependencies among components.

Modularization choices can be based on strategic modularity drivers, such as presented by Erixon et al. (1996). In this method of Erixon et al. (1996), components are evaluated one by one against certain criteria, so called modularity drivers. However, basing modularization solely on modularity drivers may not necessarily result in modules that are practically implementable. This is because the drivers do not take in account any physical representation or component dependencies of the system it is considering.

When looking at the DSM modeling tool, modularization can be based on the DSM clustering. However, basing modules solely on the DSM clustering does most likely not provide modules that offer a high degree of reusability. This is because the DSM offers clusters, so modules, based on dependencies. These proposed modules do not necessarily align with the similarities in modularity driver values of the components.

This study integrates both approaches, striving to generate practical clusters of components that consider the dependencies among the components while also taking into account the shared values for the modularity drivers. So, this research utilizes the modularity drivers as an extra input for the DSM tool. The approach in this research focuses on the modularity drivers that promote design for reusability. To generate clusters that represent practical implementable modules, constraints will be integrated into the DSM clustering. These constraints will represent restrictions that have to be taken into account when modularizing. For example, when two components should not be placed into the same module for safety reasons.

The method in this study uses the DSM clustering algorithm IGTA+. IGTA+, developed by Borjesson and Hölttä-Otto (2012) and Borjesson and Sellgren (2013), is a modification of the original IGTA algorithm of Thebeau (2001). IGTA and IGTA+ have widely been applied to use cases in literature. They have been utilized in the DSM clustering of elevators (Thebeau, 2001), gas turbines (Sharman et al., 2002), electrical trains (Sinha et al., 2020), medical devices (Hölltä and Salonen, 2003) and many more cases in literature. The IGTA and IGTA+ algorithms take in account the dependencies among the components that are considered in the DSM and then build clusters based on these dependencies. In order to design for reusability, these clusters are useful but are even more useful when the modularity drivers, that are desired, are taken in account when clustering the DSM. Which is proposed in the approach of this study. This research builds on previous work by Borjesson and Hölttä-Otto (2014) regarding the integration of modularity drivers into the clustering algorithm. Regarding the implementation of the component-to-component constraints, this study builds on the work by Sanaei et al. (2016), Sanaei et al. (2017) and Sanaei et al. (2023).

Borjesson and Hölttä-Otto (2014) propose a module generation algorithm, R-IGTA, that builds on the original IGTA and IGTA+ algorithms (Thebeau, 2001; Borjesson and Hölttä-Otto, 2012; Borjesson and Sellgren, 2013). R-IGTA balances both module independence and product similarity, allowing a product similarity strategy to influence the coupling-driven architecture considerations. Borjesson and Hölttä-Otto (2014) utilize two matrix-based methods: the Design Structure Matrix and the Modular Function Deployment (MFD). They cluster both matrices simultaneously such that strategic considerations can be integrated into the clustering. They adjust the original objective function of IGTA, the function for TotalCost, by adding an extra value that balances the DSM and DPM/MIM as a penalty in the objective, while still attempting to minimize the TotalCost.

The study by Sanaei et al. (2016) builds on the IGTA algorithms (Thebeau, 2001; Borjesson and Hölttä-Otto, 2012), and elevates the clustering algorithm approach to consider multiple objectives and partitioning constraints. This allows a designer to incorporate constraints that determine the compatibility or incompatibility of elements that are considered in a DSM. In this study by Sanaei et al. (2016), three approaches for the incorporation of the constraints are presented.

Another article of Sanaei et al. (2017) builds further on their previous work (Sanaei et al., 2016) and presents a method for product modularization that incorporates embodiment constraints due to different levels of fields in the product. The study of Sanaei et al. (2017) introduces the concept of a constraints matrix that determines which elements should and should not to be placed together in a same module. The study of this paper will make use of the work presented by Sanaei et al. (2017).

The latest article by Sanaei et al. (2023) utilizes the extended version of IGTA+ (Sanaei et al., 2017) and also builds on the original algorithms (Thebeau, 2001; Borjesson and Hölttä-Otto, 2012). This study of Sanaei et al. (2023) introduce a DSM-based clustering algorithm that incorporates practical embodiment constraints by the use of a reinforcement learning strategy. This allows the algorithm to reach acceptable levels of optimality in a reasonable amount in the presence of constraints which is often hard to achieve with conventional algorithms like IGTA+.

3 Illustrative example

The following illustrative example is developed to demonstrate how modularity drivers and component-to-component constraints can be incorporated to modularize an airplane wing for reusability by the approach proposed in this research. An overview of the physical layout of the airplane wing with a list of the components considered in this illustrative example can be found in Figure 1 (Dorbath et al., 2013; Megson, 2007; Kroes, 2013; Sterkenburg, 2019).

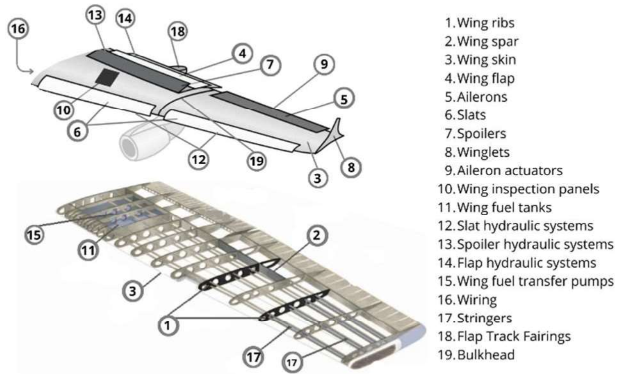


Figure 1. Decomposition of the considered airplane wing (Sterkenburg, 2019).

First a preliminary DSM is established of the airplane wing. Physical dependencies of the components have been included in this DSM. After analyzing the DSM, bus elements can be identified. Hereafter, the potential bus elements can be set, so the clustering algorithm will not place them into clusters. Then, the modularity drivers as well as the values for the component-to-component constraints will be implemented into the clustering algorithm. After the implementation of the extra input, the clustering algorithm will generate a clustered DSM providing clusters based on the similarities in modularity driver values, component dependencies and component-to-component constraints.

Bus elements

Components that have a great extent of dependencies/interactions with the rest of the components in the DSM can be assigned as so called bus elements (Browning, 2016). Because bus elements work as system integrators, they can be distinguished from clusters. When using a DSM as a tool to modularize physical modules, allowing local bus elements to be clustered among the other components is also a consideration. This is because the bus element will most likely connect the components in the cluster. This will make the cluster suitable to be a physical module with the bus element as base. However, allowing system-wide bus components to be in a module, may cause problems with the disassembly of the respective modules. System-wide bus elements are typically connected to many of the components in the system. So when placing them in clusters, they most likely also have dependencies beyond the cluster. This is a consideration that the designer should take into account. This illustrative example will look at the results of including bus elements in clusters and results that include them as separate bus elements.

3.1 Integration of modularity drivers

All components of a system can be scored on modularity drivers. The clustering seeks components that have similar values for a modularity driver, to be put into a module together. Since this study focuses on design for reusability, the chosen drivers focus on this as well. The values for the modularity drivers are implemented by means of the method of Borjesson and Hölttä-Otto (2014). An elaboration on this method is presented in the methods section above.

The number of considered components should be taken into account when deciding on the number of modularity drivers to integrate. The effect of integrating an extra modularity driver into the clustering algorithm gets less when more drivers are added. The relative weight of a driver keeps reducing when more drivers are added. When increasing the number of drivers to be incorporated this eventually leads to the same clustering outcome. This is because no more optimal clusters can be found. When this happened, this may be an indication that too many drivers are considered at the same time. In this illustrative example 19 components are considered. This means just a few modularity drivers can be taken in account. There is a way to go about this. Some drivers have overlapping features. As can be seen in the strategic modularity driver overview presented by Erixon (1996), these drivers fall into sections. Modularity drivers that have overlapping features are placed under a collective section. A designer can choose to include the collective sections instead of the separate modularity drivers. This has also been done in the airplane wing example.

The chosen drivers in this example are 1) product development, 2) attachment and 3) after sales. The first driver 'product development' is a generalized driver. This generalized driver comprises the drivers, carryover and technology push which are of importance in this example. The two drivers can be found in the modularity driver overview developed by Erixon (1996). The driver carryover assesses whether the design of a component can be reused from an earlier generation of a product to a new generation or from one product family to another. This means the drawing/model is reused, but not the actual component. A high level of carryover promotes reusability since the design of the component will remain the same. This means there is no need for a redesigned component. The driver technology push rates whether a component is likely to go through a technology shift during its life cycle because customer demands will change radically (Erixon, 1996). A low level of technology push will promote reusability. Since very few new technology requirements for the components will arise so its design can remain largely the same. All components of the airplane wing considered in this study have been scored on a scale of 0-2 for both the carryover and the technology push driver. Since the effects of technology push and carryover are in opposite directions, the values for technology push have been reversed on the scale of 0-2. That is, a component with a value of 2 for the technology push driver, is represented in the clustering by a reverse value of 0. Subsequently, the mean value for the two drivers, carryover and technology push, for each component separately are taken. These mean values are normalized to a scale from 0-1 and rounded off to an integer if necessary. This is done for the ease of implementation into the clustering algorithm to incorporate the modularity drivers.

The second modularity driver that is applied is the 'attachment' driver. The airplane wing example distinguishes between welded attachment and not welded attachment. The welded attachment is considered a relatively permanent fastening method, in contrast to other attachment techniques, such as bolts, which can more easily be dismantled. This distinction is useful when looking at the reusability. Prior to the reuse phase, the system must be disassembled into separate modules to allow the secondary use (Chu et al., 2009). When components with the same attachment method are put together in a module, it means that there is only one way of disassembly required for this module. That is why it is useful to take the attachment method in account when designing for reusability.

The generalized driver 'after sales' comprises the drivers 'service/maintenance/ease of replace' and 'recycling'. The service/maintenance/ease of replace driver assesses whether a component is easily detachable without the removal of other components, which simplifies the service repair or reusability (Erixon, 1996). A high value for this driver promotes reusability since for a module or component to be reused it must first be detached. The recycling driver assesses whether a component contains a material that will be separated before scrapping at product end of life (Erixon, 1996). Insight into this driver is useful when designing for reusability to gather information regarding whether a component can be reused material wise. A high value for this driver implies that the component is likely to contain materials that will be separated for recycling at the product's end of life. This naturally promotes reuse. All components have been scored for both the service/maintenance/ease of replace and for the recycling driver on a scale of 0-2. Hereafter, the mean of these values for the two drivers of each component are calculated and converted to a scale from 0-1, rounded off to an integer if necessary.

3.2 Integration of constraints

There are certain components in a system or product that can best not be close to each other due to for example safety reasons. These constraints can constitute a significant driving factor during product architecture decisions (Sanaei et al., 2015). The constraints for this study are included into a matrix referred to as the constraints matrix. The constraints matrix is a square matrix with identically labeled rows and columns, where each row/column denotes a component. If two component elements may not be placed into the same cluster their entry is set to zero (incompatible), if it does not matter their entry is set to one (compatible) (Sanaei et al., 2017). The values for these constraints are binary, the components can either be in a cluster together or cannot. The constraints are implemented by means of the methodology presented in the work of Sanaei et al. (2017). An overview of the components of the airplane wing that cannot be placed together in a module is presented in Table 1. The pairs of components presented in Table 1 are represented by an entry value of zero in the constraint matrix, while all other component-to-component entries are given a value of one.

Table 1. Component-to-component constraints (components that cannot be placed together in a module.

Wing fuel tanks	↔	Slat hydraulic systems
Wing fuel tanks	↔	Spoiler hydraulic systems
Wing fuel tanks	↔	Flap hydraulic systems

3.3 DSM models of the illustrative example

The preliminary DSM of the considered airplane wing is presented in Figure 2. This is the DSM without the inclusion of the constraints, bus elements and modularity drivers. The components 'Wing skin' and 'Wiring' can be identified as potential bus element. First this paper will analyze the modularity for reusability without the inclusion of the bus elements to present the method. Hereafter, in the final proposed DSM, the introduction of the bus elements will be considered.

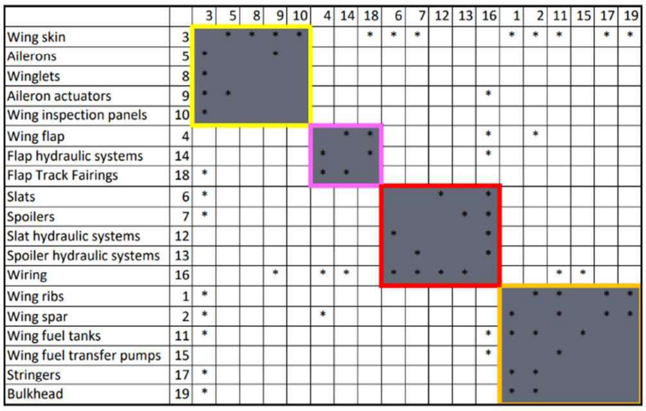


Figure 2. Design Structure Matrix of the airplane wing depicted in Figure 1, clustering without the introduction of modularity drivers.

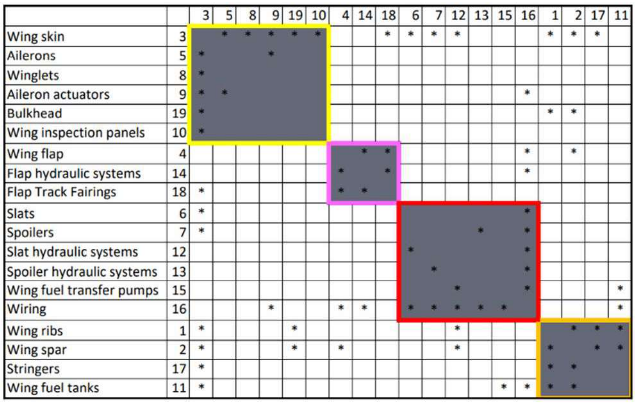


Figure 3. Design Structure Matrix of the airplane wing, clustered with inclusion of the product development modularity driver.

3.3.1 Product development driver

The first modularity driver, the product development driver, is now added to the model. When comparing the re-clustered DSM, presented in Figure 3, to the initial DSM of Figure 2, it can be seen the component 'wing fuel transfer pumps' is now placed into a different module. That is because it has a similar value for the product development driver compared to the components of the red cluster. The cluster indicated by orange contains components with a high value for the product development driver. This indicates that their carryover value is high and their technology push value is low. The module will most likely be able to be reused for a longer period of time since there is a little need to replace the components in this module with next generation components. Since the component 'wing fuel transfer pumps’ does not match this value for the product development driver to the other components in the orange module, it is placed into a different module, and clustered with the components that share the same value for the driver and with which they share dependencies.

3.3.2 Component-to-component constraints

Next, the component-to-component constraints are included in addition to the product development driver. The newly generated DSM with the inclusion of the constraints is presented in Figure 4. The component-to-component constraints that are implemented are presented in Table 1. The two components linked by the ↔ are the components that cannot be placed into the same cluster. The wing fuel tanks and wing hydraulic systems are typically kept separate. This is done to minimize the risk of contamination or fire hazards. The presence of hydraulic fluid in close proximity to fuel tanks can pose a safety risk. Separation of the components helps prevent potential hydraulic fluid leaks from coming into contact with the flammable aviation fuel. When comparing modularization of Figure 4 to Figure 3, it can be seen that now the wing fuel tanks is moved from the red cluster to the orange cluster, meeting the imposed constraints.

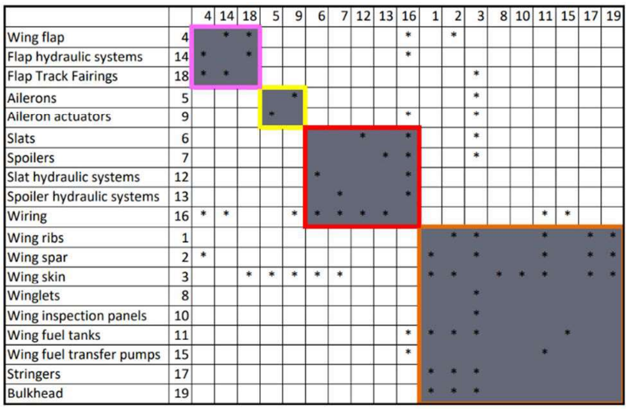


Figure 4. Design Structure Matrix of the airplane wing, clustered with inclusion of the component-to-component constraints and the product development driver.

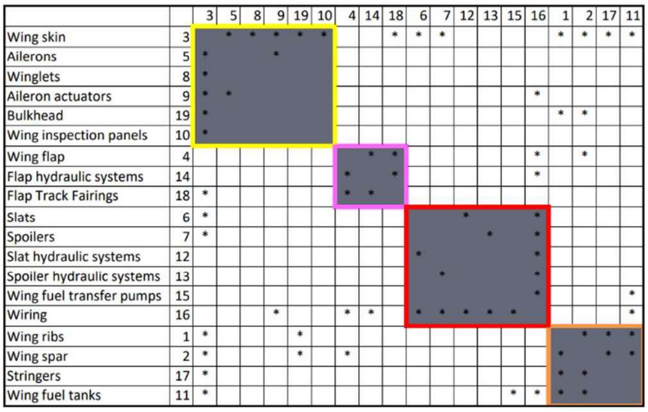


Figure 5. Design Structure Matrix of the airplane wing, clustered with the inclusion of the component-to-component constraints, the product development driver and the attachment driver.

3.3.3 Product development and attachment driver

The next modularity driver, the attachment driver is now added to the model. The resulting DSM is presented in Figure 5. The components that are welded are 'Wing ribs', 'Wing spar', 'Wing fuel tanks' and the 'Stringers'. As can be seen in Figure 5, these components are now placed into the same cluster. No other components are placed in the cluster with them. As can be seen in the situation where the attachment driver was not yet taken in account multiple different components were placed in the cluster with them. Now that the modularity driver attachment has been incorporated in the minimization criterion of the clustering algorithm this is not the case anymore. This is useful for reusability since now all modules contain components that match regarding their way of attachment. This means that for disassembly a module can be disassembled by means of the same method.

Furthermore, when comparing Figure 4 and Figure 5, the wing skin component is placed in a different cluster. This is due to the product development modularity driver. It can also be seen that now the winglets component and the wing inspection panels component are placed in this cluster. Which have the same values for the product development driver. The presented clustering matches the attachment driver completely and matches the product development driver for three of the four modules. The advantage of grouping components together regarding their attachment is that the respective modules can be disassembled by means of the same method. When matching on the product development driver the components have a similar life-time before replacement by a second generation component.

3.3.4 Product development, attachment and after-sales driver

The final modularity driver that is included in the clustering is after sales, the DSM is presented in Figure 6. The clustering configuration in Figure 6 is the same as in Figure 2. This is an indication that too many modularity drivers are considered at the same time for them to still have an individual effect. The relative contribution of a driver to the clustering objective criterion reduces when more drivers are added. The final DSM will integrate the first two drivers as the final modularity drivers since in this illustrative example they are considered most valuable.

		3	5	8	9	10	4	14	18	6	7	12	13	16	1	2	11	15	17	19
Wing skin	3		*	*	*	*			*	*	*				*	*	*		*	*
Ailerons	5	*			*															
Winglets	8	*																		
Aileron actuators	9	*	*											*						
Wing inspection panels	10	*																		
Wing flap	4							*	*					*		*				
Flap hydraulic systems	14						*		*					*						
Flap Track Fairings	18	*					*	*												
Slats	6	*										*		*						
Spoilers	7	*											*	*						
Slat hydraulic systems	12									*				*						
Spoiler hydraulic systems	13										*			*						
Wiring	16				*		*	*		*	*	*	*				*	*		
Wing ribs	1	*														*	*		*	*
Wing spar	2	*					*								*		*		*	*
Wing fuel tanks	11	*												*	*	*		*		
Wing fuel transfer pumps	15													*			*			
Stringers	17	*													*	*				
Bulkhead	19	*													*	*				

Figure 6. Design Structure Matrix of the airplane wing, clustered with inclusion of component-to-component constraints, the product development driver, the attachment driver, and the after-sales driver.

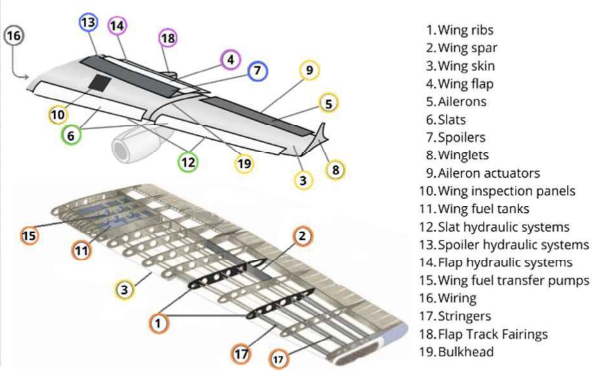
3.4 Results

The different outcomes of the DSM clustering lead to multiple different clustering configurations from the integration of the constraints, bus elements and multiple drivers considered in this study. Not all these configurations are of the same value. Each configuration brings its own set of advantages and challenges, and their significance may vary depending on specific criteria. A designer should evaluate a configuration in the context of its goals and requirements to determine the most suitable option for implementation. Such an evaluation is presented below for the airplane wing example.

The final proposed clustering fit for reusability is presented in Figure 7. The DSM model is presented in Figure 7(a) and its accompanying model configuration is presented in Figure 7(b). The final DSM has been clustered using the product development and the attachment drivers together with the component-to-component constraints. The wiring component is taken to be the bus element in this DSM. Product development and attachment are considered more important drivers for modularity than after sales. The previous section has shown that adding after sales as third modular driver obfuscates the clustering results, and is therefore left out of further consideration.

There are two candidate bus elements in this example; the wing skin and the wiring. It is the choice of the designer whether to explicitly define bus elements in the system architecture or not. It depends on the component characteristics whether or not it is potentially advantageous to treat an integrating element as a separate bus element or include it in one of the module clusters. The wing skin is taken part of wing construction module (yellow cluster in Figure 7(a)). The wing skin is in the outer surface of the wing and has a sturdy composition and inherent structural integrity. The wing skin's robust construction provides a foundation for various modular applications. The wiring is defined as a separate bus element not assigned to any of the other modules. This wiring component has a flexible shape and is integrated all over and in the middle of the wing. Furthermore, the wiring design should be such that it facilitates easy connection and disconnection with the other modules.

		16	4	14	18	6	12	7	13	1	2	11	15	17	3	5	8	9	10	19
Wiring	16		*	*		*	*	*	*			*	*					*		
Wing flap	4	*		*	*						*									
Flap hydraulic systems	14	*	*		*															
Flap Track Fairings	18		*	*											*					
Slats	6	*					*								*					
Slat hydraulic systems	12	*				*														
Spoilers	7	*							*						*					
Spoiler hydraulic systems	13	*						*												
Wing ribs	1										*	*		*	*					*
Wing spar	2		*							*		*		*	*					*
Wing fuel tanks	11	*								*	*		*		*					
Wing fuel transfer pumps	15	*										*								
Stringers	17									*	*				*					
Wing skin	3				*	*		*		*	*	*		*		*	*	*	*	*
Ailerons	5														*			*		
Winglets	8														*					
Aileron actuators	9	*													*	*				
Wing inspection panels	10														*					
Bulkhead	19									*	*				*					



(a) (b)

Figure 7. Final proposed modularization for the airplane wing, obtained by clustering the design structure matrix with inclusion of component-to-component constraints, the product development driver, the attachment driver, and 'Wiring' as bus element.

The final modular configuration presents five modules with wiring as a separate bus element, all the component-to-component constraints are met. The components of the cluster indicated by the orange marking in Figure 7(b), share all drivers except the component 'wing fuel transfer pumps'. The ‘wing fuel transfer pumps’ are placed in this cluster since the module has only two interfaces; one with a component in the orange cluster and one with the wiring component which is treated as bus element. Considering the attachment driver, the only option is to put the wing fuel transfer pumps into the cluster with the welded components. Constraint-wise there is no objective to do this. In such situations a designer has to make the trade off to include or exclude certain components in a cluster. In this example the wing fuel transfer pumps will be kept in the cluster since the module shares the product development driver. This indicates that clustered component in the orange cluster have similar values for carryover value and technology push. The module will most likely be able to be reused for a longer period of time since there is a little need to replace the components with next generation components.

In Figure 7, the components in the purple, green, and blue clusters share both, product development and attachment drivers. This means that the components in these modules match the other components for the drivers. The clusters of these components can be treated as modules for reuse. The last, yellow, cluster has elements that all have the same attachment driver.

The final modularization for reusability presented in Figure 7 differs from the modularization of the DSM displayed in Figure 8 which has been obtained by clustering using component-to-component constraints only without any additional modular drivers, but with wiring as bus element. The clusters in Figure 8 do not match most of the values of the modular driver, making this modularization less suitable for reusability. With the modular drivers in place, modules are obtained as displayed in Figure 7 which are more suitable for reusability.

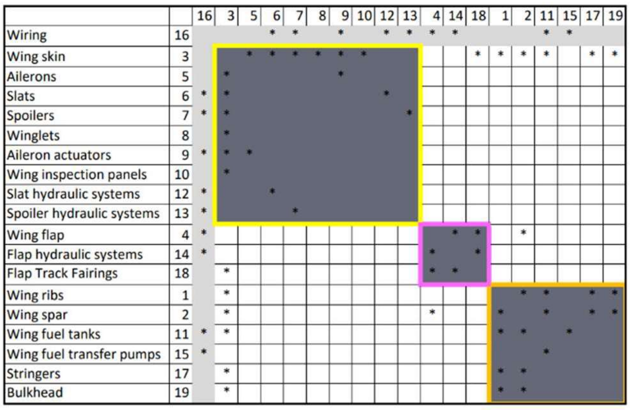


Figure 8. Modularization of the airplane wing, obtained by clustering the Design Structure Matrix with inclusion of the component-to-component constraints and wiring as bus element.

4 Discussion and future work

Clustering the DSM with the modular drivers in place provides insights how to optimize the design structure to enhance reusability. Insights are obtained on how design choices for components affect the various criteria for reusability. The clustering method also allows focus on the reuse of a few selected components. Subsequently, the DSM can assist in identifying the impact of changes in one component onto other components, when pursuing design for reusability.

4.1 Limitations and suggestions for future work

The data the illustrative example is based on was gathered from open source resources. The data representing the airplane wing may be incomplete or overly simplified. However, the example problem is deemed representative for the purpose of demonstrating the method proposed in the paper. The method’s use is not limited to this example. A second limitation is that this study only takes disassembly into account to a small extend. There is a usefulness of the DSM with respect to disassembly of the system. When modules or components will be reused, disassembly becomes an important factor for a designer. As DSMs provide a visual representation of dependencies among components and modules, they provide valuable information for the disassembly phase for several purposes. The process of disassembly is not within the scope of this study. Potential future work incorporating this would be a useful development.

Third, the DSMs of this illustrative example focus only on physical dependencies. A more elaborate DSM, including different kinds of dependencies and incorporating these in the clustering method may provide new avenues for more detailed analysis of modularization for reusability.

Fourth, this study does not take into account limitations such as safety requirements for reuse of components and materials. This is a factor that can cause an obstacle for certain systems that contain strict safety requirements. This is a potential subject for future work.

Fifth, the illustrative example in this study suggests using the attachment of components as a driver for the modularization for reusability. However, the illustrative example focusses on a system, the airplane wing, as it is designed before taking reusability into account. When a system is designed with the intent of reusability, different choices would probably been made regarding attachment of certain components. An alternative route would be to first do a modularity for re-usability analysis, and subsequently decide which attachment methods are most appropriate for the resulting clusters and their interfaces.

Another limitation regarding the illustrative example is that certain component groups have been have been treated as single elements in the DSM. For example, the fuel pumps component, the wiring component, and the wing skin component. This has been done to keep the example simple, but has a side effect that it creates artificial bus elements in the DSM. As a consequence, the dependency network has become more dense. By introducing multiple instances of these class elements, i.e., adopt a pure part-whole decomposition, one would possibly be able to optimize towards repetitive modularity clusters similar in composition and structure, which is advantageous for re-use. This is a highly interesting observation by one of the anonymous reviewers, which is recommended for future work.

5 Conclusions

The illustrative airplane wing example demonstrates the method proposed by Sanaei et al. (2016, 2017) can be adapted and exploited to modularize a system for reusability. The clustering approach incorporates modularity drivers in the clustering objective to base modularization on component reusability characteristics, such as product development, attachment methods, after sales and component-to-component constraints. The outcome of the illustrative example presents a system modularization that is more amiable for reusability than the clustering obtained without the modularity drivers. The method presented in this research enables designers and engineers to modularize a system for reusability based on modularity drivers and component dependencies while taking constraint into account.

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