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Modeling Requirements Propagation to Generate Solutions for Minimizing Mass

Thulasiram Ezhilan
Clemson University, TEZHILA@CLEMSON.EDU

MODELING REQUIREMENTS PROPAGATION TO GENERATE SOLUTIONS FOR MINIMIZING MASS

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Thulasiram Ezhilan
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Accepted by:
Dr. Georges M Fadel, Committee Chair
Dr. Joshua D Summers
Dr. Gregory M Mocko

ABSTRACT

This thesis investigates the issue of weight reduction in moderately complex systems by addressing how to cascade the requirements to the individual components. Though mass can be reduced using different techniques such as material substitution or structural optimization; a systematic method for allocating mass as a function of requirements is necessary to provide novel alternate solutions that enable reduction of mass of the system while satisfying the requirements and tests governing them. Such a method can be developed by exploring different aspects of achieving weight reduction through change propagation in the parameters/elements governing the system. Though efforts have been made to relate the propagation of change in complex systems in terms of its impact on the system, current research has not yet developed a systematic method to generate novel solutions for mass reduction at the component level and assembly level by modeling the requirements propagation. The hypothesis to validate in this thesis is that a systematic method would facilitate generation of solutions at an assembly level of the system by eliminating non-functional requirements, merging functions or finding alternate working principles and their embodiment that satisfy the functionalities, requirements and tests imposed on that system. A case study is conducted on the BMW Z4 cooling system and it is observed that additional solutions are generated at a higher level of the hierarchy. Also, a visualization tool and accompanying algorithms to generate solutions at the component level using the multiple matrix method (a method developed by the research group as a part of the BMW project) has been developed to facilitate change propagation and traceability.

DEDICATION

This thesis is dedicated to the researchers that do challenging research in the design methodology domain of the engineering design field and researchers who have contributed to the development of design methods till date. This thesis is also dedicated to my parents.

ACKNOWLEDGEMENTS

I am extremely grateful to my advisor, Dr. Georges Fadel for his constant support, guidance, constructive feedback and encouragement throughout my research work and motivating me to make a meaningful contribution to the field of engineering design. I am thankful to him for being very flexible with time schedules. Also, I am thankful to Dr. Fadel for considering me in the BMW requirements modeling project and also involving me in many other interesting activities in his Clemson Research in Engineering Design and Optimization (CREDO) laboratory. I would like to extend my sincere thanks to Dr. Joshua Summers and Dr. Gregory Mocko (who were part of BMW project) for their encouragement, feedback and support throughout the project. I am also grateful to Dr. Jonathan Maier, research associate in BMW project, for providing his timely and constant help, valuable feedback and support throughout this research. I would like to thank Mrs. Barbara Ramirez for rendering her help to organize this thesis. I would like to thank BMW for funding the BMW requirements modeling project. I would also like to thank Mr. Norbert Seyr, vehicle technology representative from BMW, for his support. Finally, I would like to thank other students in AID, CREDO and EIML laboratories for their co-operation.

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CHAPTER 1

PROBLEM STATEMENT AND LITERATURE REVIEW

1.1 Problem Statement

The need to reduce the mass of products is receiving much attention in the engineering design field. Reduced mass leads to lower materials and shipping costs, improved efficiency for dynamic systems, less environmental impact, and lower retirement costs [1, 2]. Mass reduction is currently accomplished by material substitution or by structural optimization. To further reduce mass, it is important to know the system/sub-system under analysis, in particular the different domains governing the system. These different domains include requirements, functions, components, and tests. In the initial stages of design, product development is governed by requirements, which are translated into the system functionality that can be represented by a black box diagram. This functionality is typically achieved by integrating various assemblies and their components. These components are described by their parameters as they govern the physical embodiment. If components are optimized by changing some of their parameters in order to reduce mass, then the modified components should satisfy the functional requirements they affect. This verification is performed according to system level tests or to tests that are component-specific. To perform these tests, it is important to know the test measures. Since all these entities governing a system are interrelated, a change in one affects the other, and a sequence: requirements, functions, components, component parameters, test measures, tests can be assumed. Specifically, change in the mass of a system may be accomplished by reducing the mass of components or by combining functions in fewer components, thereby eliminating some without affecting the functionality of the system. To ensure that performing the above steps does not have any negative impact on the other elements that govern the system, it is necessary to have a good model that allows the user to trace the correlation between all entities of a system. To visualize the traceability across various domains, a computer aided visualization tool is required. Further, a systematic method is required to generate solutions that potentially reduce the mass of the system at the component level and at the assembly level that allows:

- Creation of models linking requirements, functions, components, and tests
- Examination of the effects of changing any of these entities on the others
- Determination of what effect changes in the model would have on the system mass

This thesis will address these issues aiming to generate feasible solutions for reducing the mass of the moderately complex systems/sub-systems under investigation.

1.2. Literature Review

A literature review was performed on various requirements modeling approaches in requirement engineering, software engineering and systems engineering to understand the important terminologies and methods associated with these topics. Also, several requirements management and modeling software with different models for traceability were identified and studied. They are summarized in two different sub-sections. Section 1.2.1 deals with the review of the various requirements modeling approaches in engineering design, requirements engineering and software engineering. Section 1.2.2 deals with the review of various requirements management and modeling software available in software engineering and systems engineering.

1.2.1 Requirements Modeling Approaches

The Product Data Specification (PDS) method advocated by Pugh (1991) records and tracks requirements, creating an evolutionary document matching the characteristics of the design as it develops [3]. Requirements related to performance, the environment, ergonomics, maintenance, and safety of both the target design and competitor's designs are captured. This document serves primarily to verify whether all the constraints and criteria initially identified have been considered.

Lubars et al., (1992) reviewed the field of requirements modeling, performing a field study of ten organizations to discover how they define, interpret, analyze, and use requirements in the development of software systems and products [4]. Their methods involved collecting the requirements, including the source, additional information gathered through interviews, analysis of organizational procedures, the applications involved, and the customers. These researchers' focus was on solving organizational problems arising from the mismanagement of requirements.

Easterbrook et al., (1998) investigated formal methods to model requirements. They proposed an approach to provide cost effective techniques for requirements specification [5]. They dealt with the test requirements for fault preventive systems and the expected behavior of the embedded software systems for fault preventive systems in spacecraft. They discussed the application of formal methods to requirements modeling with three case studies, thereby enhancing the verification and validation process.

Lee and Kuo (1998) developed an approach for performing requirement trade-off analysis in complex systems. Their requirements classification scheme analyzing the heterogeneous requirements identifies the relationships between the requirements [6]. The requirements that conflict or seem to be irrelevant are analyzed for trade-offs. The researchers used parameterized aggregation operators to combine or perform trade-off analysis of the requirements. Their framework provides a formal way to analyze and model the conflicts between the requirements.

The MOOSE method advocated by Gershenson, et al. (1999) includes a taxonomy classifying corporate requirements such as manufacturing, marketing, service, or financial, that impact product design [7]. These researchers considered the taxonomy to be an organized method of gathering, managing and retrieving the requirements. MOOSE was developed to facilitate a broader, clearer form of Quality Function Deployment (QFD).

Rolland and Prakash, in their paper “From Conceptual Modeling to Requirement Engineering” (2000) argued that conceptual modeling incorporates a broad view of information systems requirements engineering exploring the objectives of different stakeholders and the activities [8]. This allowed them to derive purposeful system requirements and therefore lead to better quality systems (that meet the requirements of the users). In contrast to conceptual modeling, requirements engineering emphasizes the engineering process employed. The requirements engineering model developed by Roland and Prakash is shown in Figure 1.1.

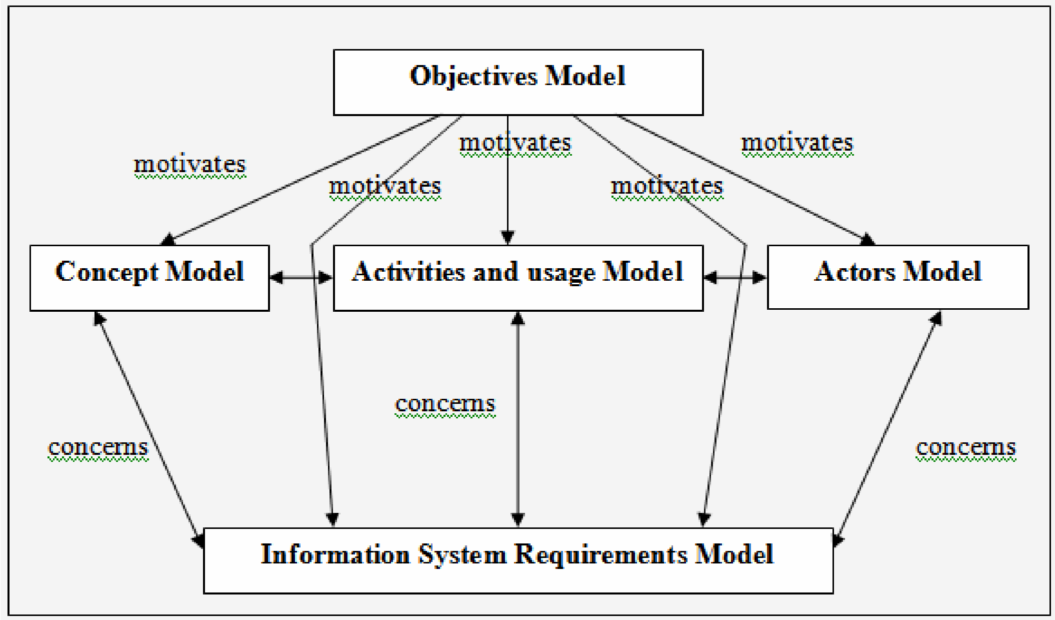


Figure 1.1 Requirements engineering model of Rolland and Prakesh (2000)

Ramesh and Jarke (2001) discussed reference models for requirements traceability, the purpose of which is to reduce significantly the task of creating application-specific representations of systems [9]. According to their method, the user selects relevant parts from a reference model, adapts them to the problem at hand, and configures a specific solution from the adapted parts. Their method uses proprietary software including sub-modules for requirements management, requirements rationale, design allocation, and compliance verification. A representation of the requirements management sub-module is shown in Figure 1.2.

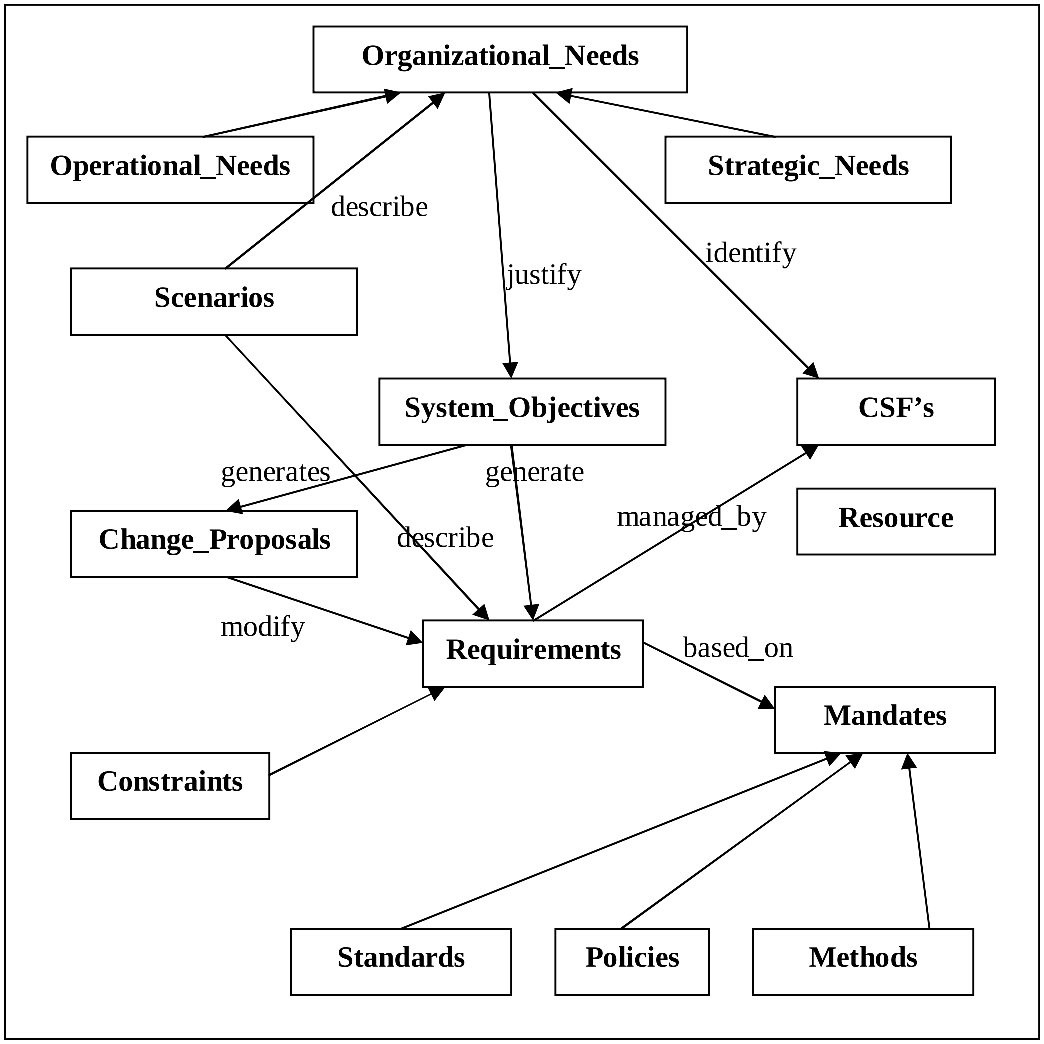


Figure 1.2 Requirements Management Sub-Module developed by Ramesh and Jarke using SLATE software (2001)

Laguna et al.., (2002) proposed a method to specify the requirements for reuse thereby reducing the errors that occur due to incorrect requirements specification [10]. A multi viewed requirement technique that would be helpful for requirement analysis was developed earlier by Delugach (1991). Laguna et al., (2002) developed a meta-model to enhance the requirements reuse approach. Their approach focused on the requirements determination of requirements for software development.

Fu et al., (2003) studied requirements in relation to product life cycle. They categorized requirements as Voice of the Customer (VOC), market requirements, statutory requirements, corporate requirements, and realization requirements [11]. They provided a systematic framework for modeling, managing, accessing, retrieving, updating, changing, sharing and reusing the design requirements. They also discussed the impact of design requirements in the product development life cycle.

Clarkson et al., (2004) reviewed the existing literature on change propagation and conclude that no existing methods (e.g., from software engineering) are appropriate for complex mechanical engineering systems [12]. They captured the past experience of the actual design engineers as a part of their approach. They introduced a matrix-based method for predicting the likelihood, impact, and risk of changes to existing designs (i.e., variant design). They termed their model as Change Propagation Model (CPM). It is shown in Figure 1.3. Researchers interpreted the change propagation in terms of the likelihood of change and the impact of change. The researchers concluded that due to the complex nature of the engineering system (a helicopter, in their case), a comprehensive model of the system's behavior does not exist.

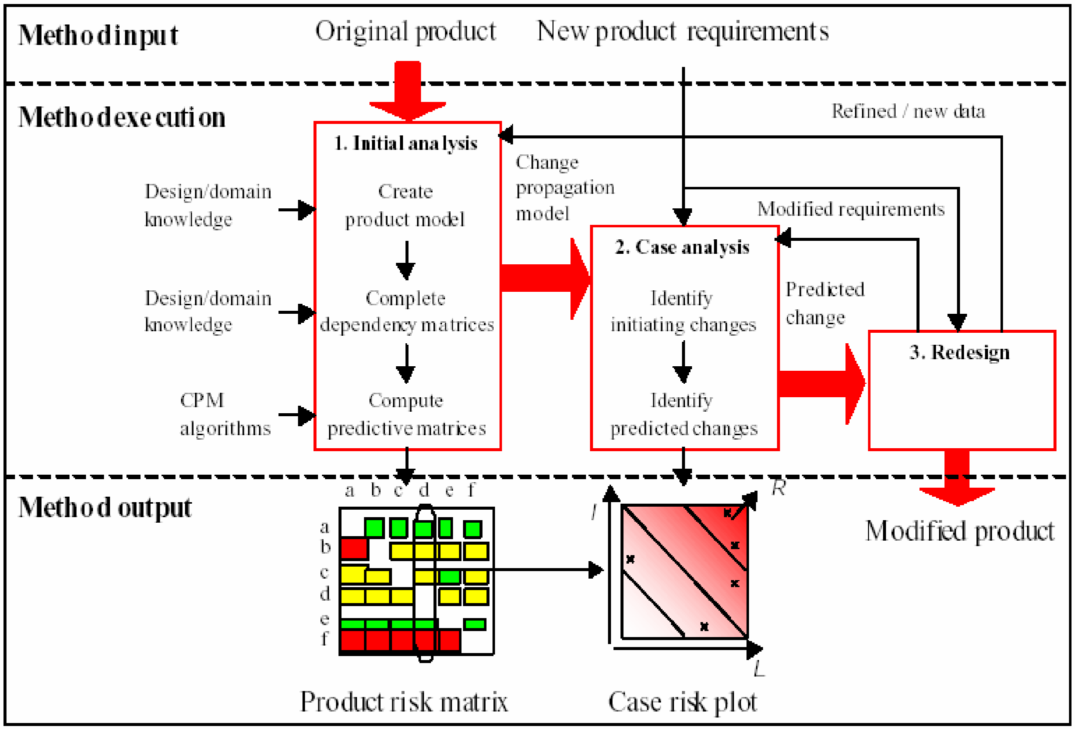


Figure 1.3 Change propagation model adopted by Clarkson et al [2004]

The representation scheme developed by Motyka (2005) shows the relationships between components in terms of eight phenomena: thermal, kinetic, fit, acoustics, electromagnetic, monetary, weight, and material [13]. Each of these is color coded in a companion diagram. However, this scheme is primarily a graphical representation of the actual components, and does not explicitly capture the requirements leading to the final component relationships.

Somé (2005) introduced a method to narrow the gap between the customers and the system development process [14]. He employed use cases to describe the behavior of a system, and to capture and document the requirements. These used cases support requirements verification, validation and clarification. Some suggested that use cases that describe the possible interactions may be used as an effective way for functional elicitation and analysis.

All the researchers recognized the criticality of requirements definition for the design of an artifact. In fact, all the researchers attempted to study the impact of these requirements on the definition of the artifact. Considering this impact, the handling of the artifacts can be recognized in different phases. They are: Requirements elicitation, analysis, allocation, propagation, tracking or traceability, verification, creation of requirements taxonomy [11, 15, and 16]. Elicitation of requirements refers to the phase of requirements determination in which an initial set of requirements for a system is discovered. It may also be defined as the process of gathering the requirements that govern the product or that are required/have to be satisfied to define the product. The analysis of requirements is an iterative process involving evaluating, decomposing, sorting, structuring and prioritizing, change processing and approval processing to refine and formalize the requirements [17, 18]. Allocation assigns the corresponding requirements to detailed processes or to the detailed elements/components of the system/product. Tracking or traceability performs continuous analysis and keeps track of the changes for the process as a whole and verification is used to check whether requirements have been met. Several authors attempted to ensure that the requirements are correctly defined and used, and introduced the need for a classification of these requirements. A taxonomy is the hierarchical classification of a large amount of information. Propagation refers to the cascading of the requirements from the system level to the subsystem or component levels to investigate the effect of the requirements on the design. Table 1.1 below summarizes the studies discussed in this section according to the various issues they claim or attempt to consider.

Table 1.1 Comparison of various requirements modeling approaches

	Elicitation	Analysis	Allocation	Traceability/ Tracking	Verification/ Validation	Taxonomy	Model	Propagation
Fu et al	Yes	Yes	Yes	Yes	Yes	No	Design model requirements is available	No
Gershenson et al (MOOSE)	Yes	Yes	No	No	No	Yes	Taxonomy may be considered as a model	No
Motyka	Yes	Yes	No	No	No	No	Complexity model	Yes
Lubras et al	Yes	Yes	No	No	Yes	No	Yes	Yes
Rolland et al	Yes	Yes	No	Yes	No	Yes	Concept model and requirements engineering model	Yes
Some	Yes	Yes	No	No	Yes	No	Use case model	No
Easterbrook	Yes	Yes	No	No	No	No	Functional concept diagram	No
Lee	Yes	Yes	Yes	No	Yes	Yes	Hierarchical aggregation structure	Yes

Table 1.1 Comparison of various requirements modeling approaches (Continued)

	Elicitation	Analysis	Allocation	Traceability/ Tracking	Verification/ Validation	Taxonomy	Model	Propagation
Laguna et al	Yes	Yes	No	No	No	No	Meta model for requirements reuse approach	Work flow-down available
Ramesh et al	Yes	Yes	Yes	Yes	Yes	No	Traceability meta model	Yes
Clarkson et al	Yes	Yes	No	Yes	Yes	No	Yes	Yes

It was observed that none of the approaches considers all the aspects in the requirements engineering process. MOOSE (based on QFD) developed by Gershenson et al and an approach proposed by Fu et al., comes close to considering all the aspects but does not capture functions, or tests or specific areas to improve such as mass. Also, no approach leads to concrete solution approaches. Some authors attempted to model the requirements and various software programs were developed to support such efforts. These are discussed in the next section.

1.2.2 Requirements Modeling Software

Having discussed the capabilities of the various requirements modeling approaches in the previous sub-section, this sub-section discusses the capabilities of various requirements modeling software. The requirements management model of SLATE is shown in Figure 1.4. It focuses on the link between the requirements, mission needs, system objectives, and decisions. Requirement traceability, design allocation and logical verification can all be performed effectively using this model. The nature of the relationship between the blocks is represented above / below the arrows. However, it does not incorporate functionality, testing, and their relation with requirements.

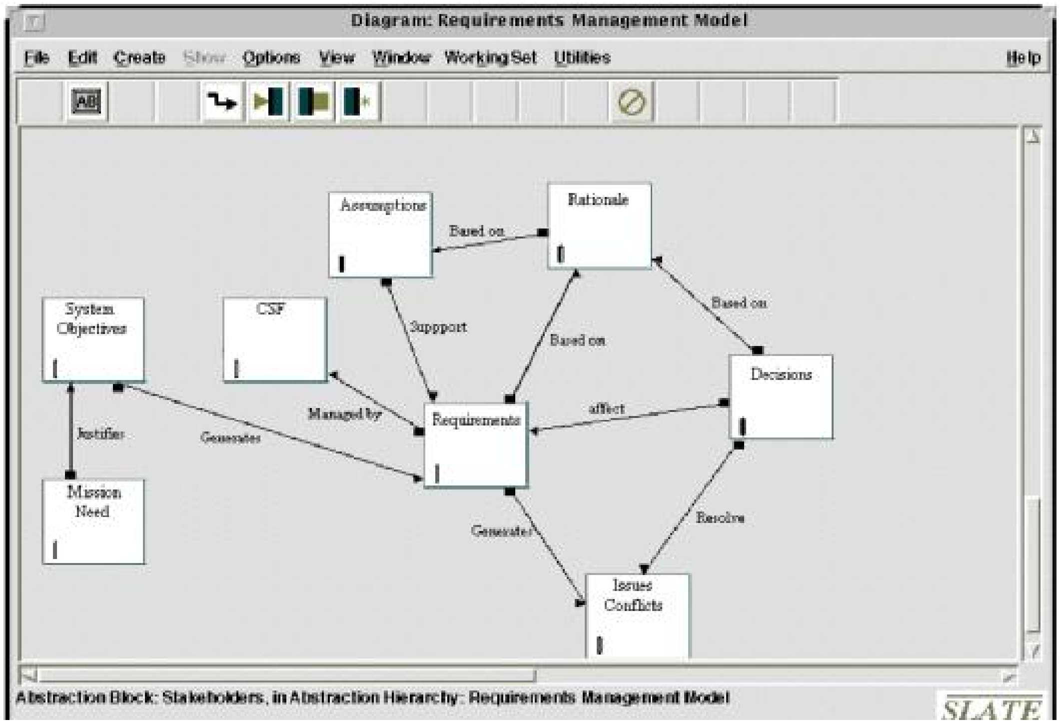


Figure 1.4 Requirements management model of SLATE [9]

In the V-model of systems engineering on which DOORS software is based [19], requirements and testing are integral to the development process, as shown in Figure 1.5. The traceability of the requirements in the V-model is shown in Figure 1.6. The customer requirements, system, subsystem and component requirements verified using their corresponding tests is represented in these figures. However, the V-model representation does not explicitly show either the components themselves, or the functions they accomplish. It primarily focuses on the requirements to tests relations.

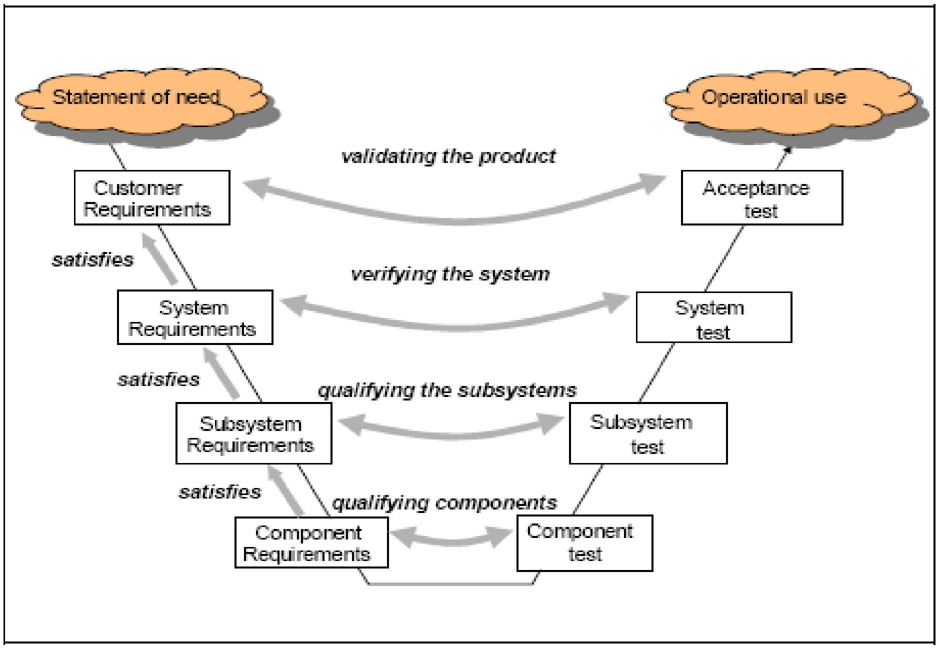


Figure 1.5 Requirements and testing in the V-model of design [19]

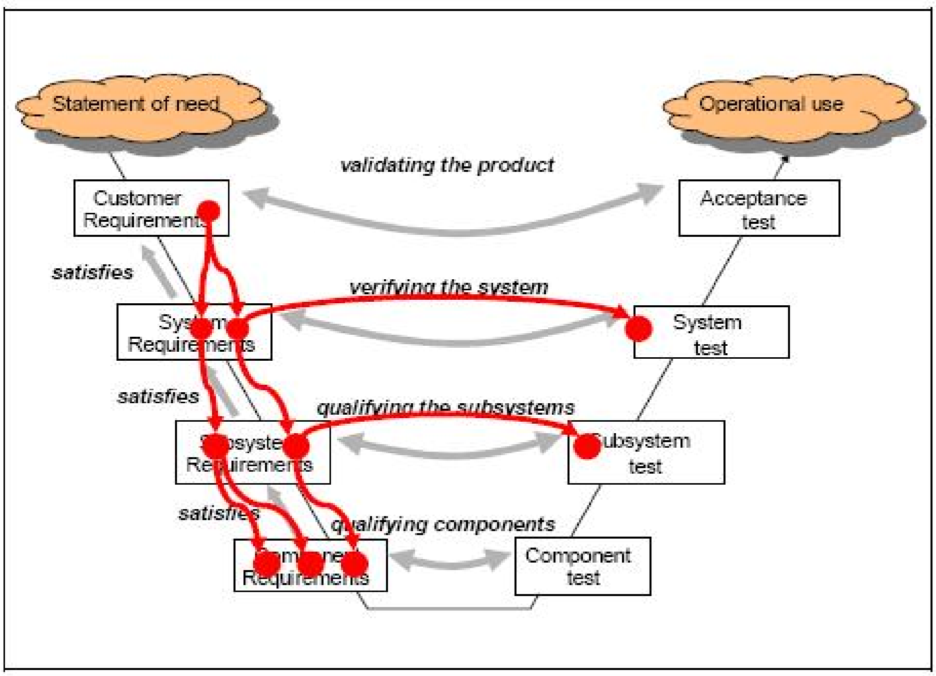


Figure 1.6 Traceability in the V-model of design [19]

This V-model of design is used by DOORS, an object-oriented requirements management software package developed by Telelogic.

SysML, the requirements management software package developed by IBM, is based on the Unified Modeling Language (UML) architecture used for software engineering. SysML recognizes six top-level categories: structure, behavior, properties, requirements, verification, and propagation. A requirement can include parameters such as an identification tag, the verification method, risk involved, the source of the requirement, and the type of the requirement [20]. Operations performed using the requirements in SysML are allocate, analyze, bind, satisfy, synthesize, trace, and verify. Figure 1.7 shows an example of a requirements hierarchy for a hybrid sports utility vehicle created in SysML.

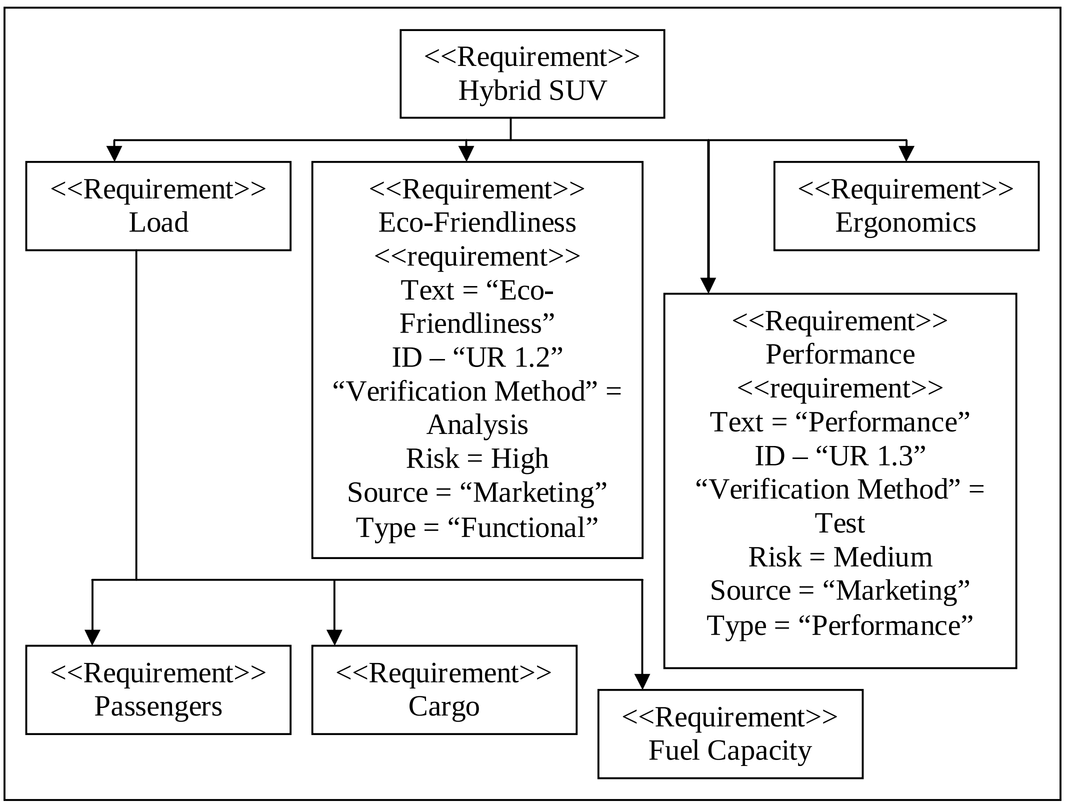


Figure 1.7 A sample of a requirements hierarchy for a hybrid SUV created in SysML [20]

Enterprise Architect (EA), a Unified Modeling Language (UML) case tool developed by Sparx systems, provides the ability to create and view requirements. It also allows the users to enter the attributes of each requirement thereby establishing a systematic approach for sorting the requirements [21]. A screenshot showing the different attributes captured using EA is shown in Figure 1.8. Also, EA has its unique requirements traceability matrix to monitor the impact of change in requirements. The relationship matrix shown in Figure 1.9, allows the creation and viewing of requirement relationships (includes use cases, interfaces, and components). However, EA lacks the potential to capture the functions that relate to the requirements or those relating to the components of the system that performs the function.

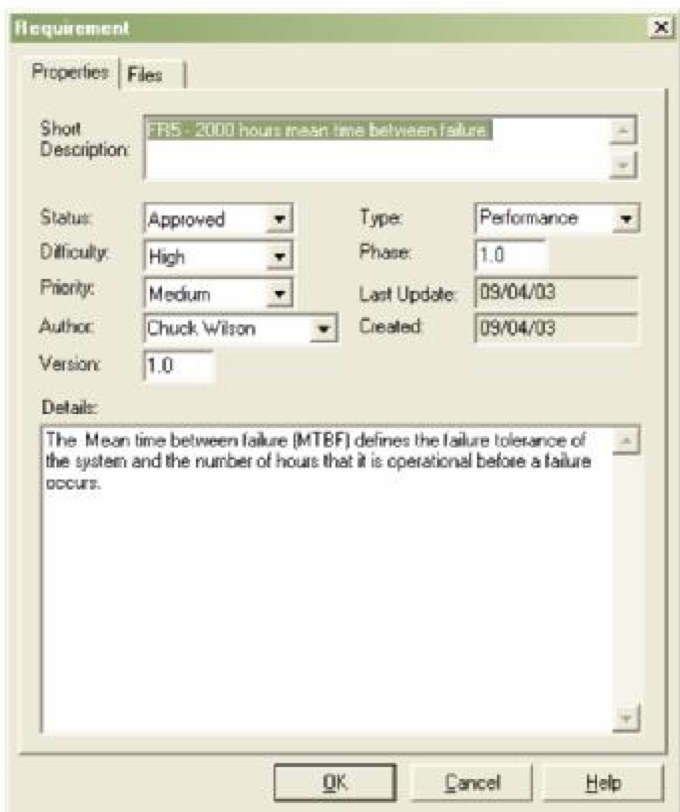


Figure 1.8 Requirement attributes in Enterprise Architect [21]

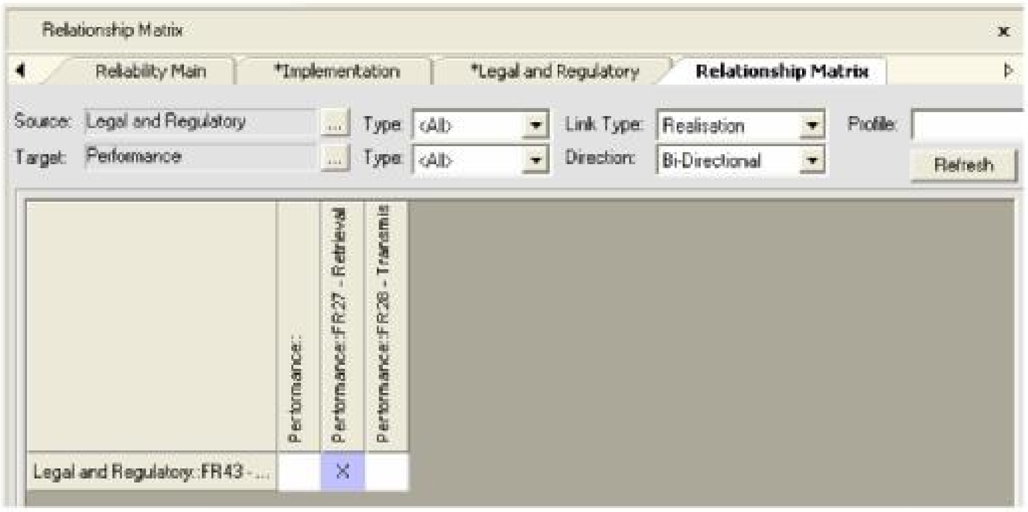


Figure 1.9 Relationship matrix in Enterprise Architect

The AP233 software tool developed by Eurostep facilitates managing, structuring, and allocating requirements as part of systems engineering [23]. This software allows representation at the system's physical and functional levels. Requirements are entered as text and assigned mathematical properties. Traceability is shown via a graphical representation scheme. Although not yet a viable module, current research focuses on implementing algorithms to show derived requirements and to test if requirements are verified for a given quantitative data. Figures 1.10 and 1.11 illustrate the application of AP 233 to a vehicle. While promising, particularly for the handing of mass values, this tool is not yet fully developed and hence was not available for use in this work.

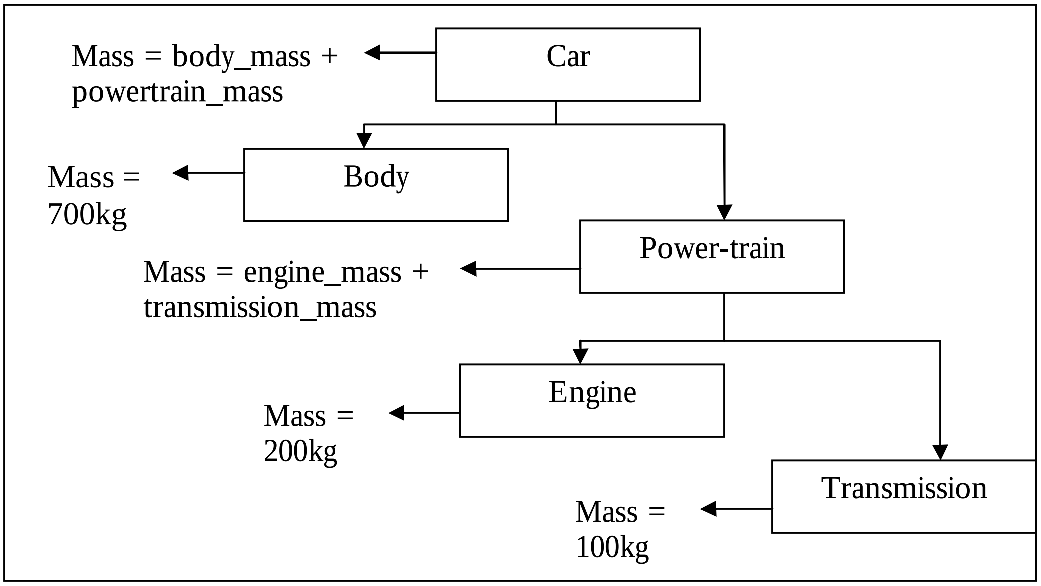


Figure 1.10 Example of algorithms that could be used in AP233 [23]

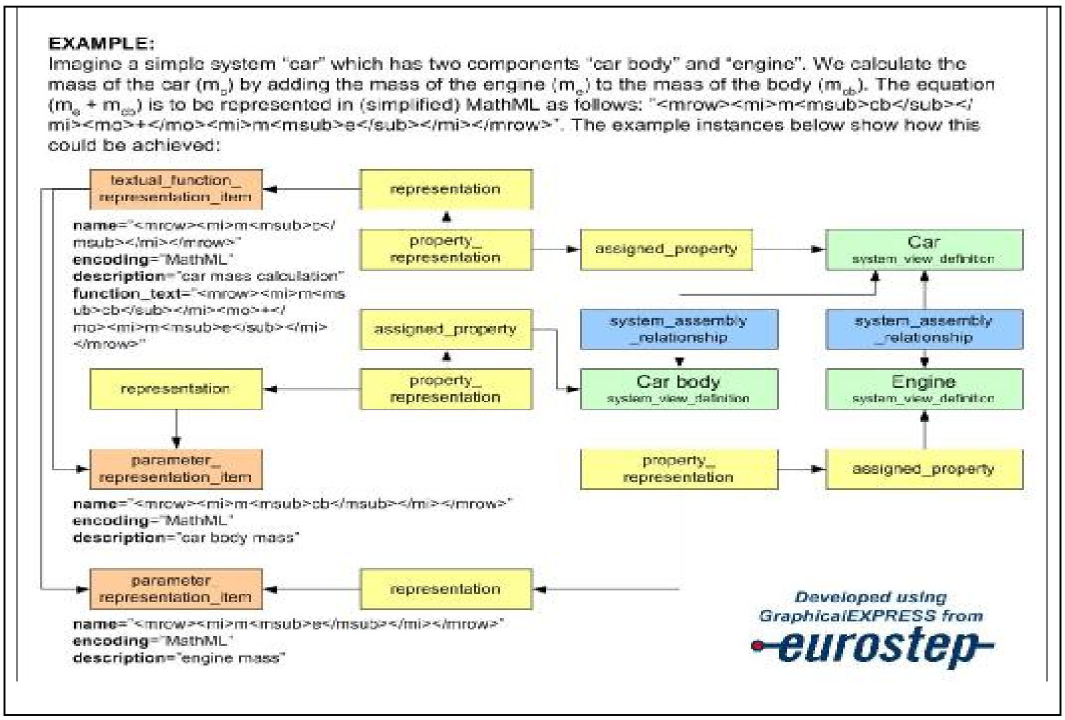


Figure 1.11 Example application of AP233 to a vehicle [23]

The requirements management software discussed in this section attempt to study various phases of the systems engineering process. They are: Requirements allocation, tracking or traceability, analysis, configuration management, change management, requirements verification and requirements specification along with portability and backend compatibility. The analysis of requirements is an iterative process involving evaluating, decomposing, sorting, structuring and prioritizing, change processing and approval processing to refine and formalize the requirements. The allocation assigns the corresponding requirements to detailed processes or to the detailed elements/components of the system/product. Tracking or traceability performs continuous analysis and keeps track of the changes for the process as a whole and verification is used to check whether requirements have been met. Interpretation of the requirements through a definite set of objects in a database is performed through configuration management. Methods used to document the requirements are performed during the requirements specification phase. Table 1.2 below summarizes the capabilities of the requirements management software discussed in this section according to the various phases of the systems engineering process.

Table 1.3 compares various requirements modeling software packages with respect to the requirements engineering terminologies defined earlier in section 1.1.

Table 1.2 Comparison of Requirements Modeling Software Packages

	Req Allocation	**Req Trace-ability**	**Req Analysis**	**Configuration management**	**Change management**	**Requirements Verification**	**Requirements specification / Documentation**
SysML	Represented in sparse matrices	Via Requirements Traceability Matrix	Using mathematical equations, charts, graphs	Via context blocks	Via stereotype that keeps track of changes	Methods including analysis, test, inspection, demonstration, and test cases	Uses Unified Modeling Language documentation as backend
DOORS	No information available	Object links provide user defined, multilevel, traceability	A set of states are associated with each requirement.	Via project baselines	Records the change history of requirements.	Via automatically generated web interface	Doc-Express is used to document, Requirements (an add-on module)
SLATE	User may allocate portions of a performance requirement	Uses trace tables	Usually, this module is coupled in SLATE and termed as traceability analysis.	Allows user to standardize all the objects in the database	Accessible parameters include requirements, parameters and documents	Verification status can be monitored by the system to automatically trigger events	Uses Frame maker or MS Word as its document generation engine
Enterprise Architect 6.0	No information available	Using Relationship Matrix	Requirement traceability is analyzed sequentially.	Via color coding	Not supported.	No information available	Report generator tool.

Table 1.3 Comparison of Requirements Modeling Software Packages with respect to requirements engineering terminologies.

Requirements Modeling Software Approaches								
	Elicitation	Analysis	Allocation	Traceability / Tracking	Verification / Validation	Taxonomy	Model	Propagation
DOORS	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
SysML	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
SLATE	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Enterprise Architect	Yes	Yes	No information available	Yes	No information available	No	Yes	No information available

It can be observed that various requirements management software to trace and manage the requirements exist. But, none of the software facilitates linking all the domains of interest. Also, mass is not explicitly captured in most. Change propagation is not directly supported in DOORS and it does not explicitly capture mass. AP233 protocol appears to be the most promising once it is implemented in a software environment, but it is not yet available.

1.3. Research Questions

From the literature review on various requirements modeling approaches and requirements management software, it was determined that no single existing modeling approach or software package provided the necessary flexibility to handle the types of requirements and operations that allows for the creation of models linking requirements, functions, components, and tests, examination of the effects of changing any of these entities on the others and determination of what effect changes in the model would have on the system mass. This leads to the research questions discussed below.

1. Can a systematic method and model, incorporating the domains that govern the system be used to generate solutions at the component level for minimizing mass?

In order to answer this question, some basic sub-questions must be answered:

- What type of an approach (matrix based approach or node link diagrams or connectivity graphs) should be adopted for creating a model?

2. Can a computer-aided visualization tool enhance or facilitate the traceability of the developed model?

3. Can a systematic method and model, incorporating the entities that govern the system be used to generate solutions at the assembly level for minimizing mass?

- How is the information gained at the lowest level of the hierarchy transferred to a higher level?

4. Can additional solutions result from considering the system at a higher level?

These research questions are answered in the subsequent chapters. This chapter frames the problem and shows that although there is significant work on handling requirements, the propagation of these to study ways to reduce mass does not exist. Research questions are posed and prepare the reader for the next chapter which deals with selecting an appropriate representation scheme for the modeling scheme.

CHAPTER 2

SELECTION OF AN APPROPRIATE REPRESENTATION SCHEME FOR THE MODEL

2.1 Introduction

The model developed for this research incorporates various domains that govern an automotive system. Traceability is necessary to ensure systematic mapping between the various domains governing a system as well as between the tests and the requirements [24, 25]. Specific to engineering design, attempting to reduce the mass of complex or semi-complex systems using a system based approach requires a robust traceability model accompanied by a systematic method. That traceability model should allow the user to:

- Trace the dependency or independency of entities.
- Analyze the effect and impact of a change in one entity on related ones.
- Facilitate capturing the designer's intuitive understanding of the system behavior.
- Have potential answers for the what-if scenarios (for example: analyzing the effect of removing a component across various domains in the model)

As can be the seen from the previous chapter, current traceability models like the V-model, do not adequately capture the necessary information about the entities governing the system. To enhance the traceability characteristic of the model, it may be better to adopt conventional approaches like the node-link diagrams, connectivity diagrams, tree structure or matrix-based approach. This chapter provides a brief overview of various representation schemes and selects a valid candidate for the model used in this research.

2.2 Node-Link Diagrams

A node-link diagram, one type of representation scheme, depicts elements or parameters of interest as nodes, with arrows to indicate the connections. Sample node link diagrams are shown in Figure 2.1. They represent the node-link diagrams of a car engine, including the links between the six main components. The relationships between the components are clear because the number of nodes is minimal. If a node-link diagram is drawn with a large number of nodes, then the representation becomes complicated and difficult to interpret. This difference is supported by user study experiments conducted by Keller et al., as they found that node-link diagrams offer better visual representation for small, uncomplicated entities but they are a complex form of representation for large systems and propagation across systems [26]. Since the systems/sub-systems considered in this research involve a large number of elements, node-link diagrams would not be the best representation scheme for the model to be developed.

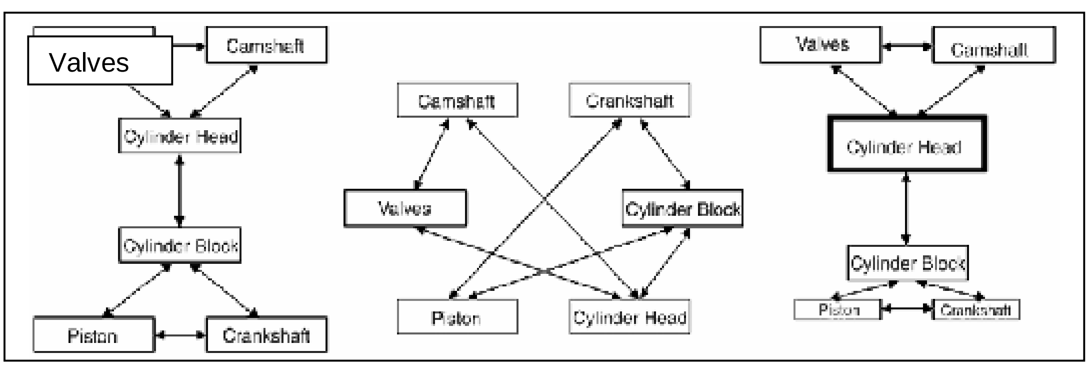
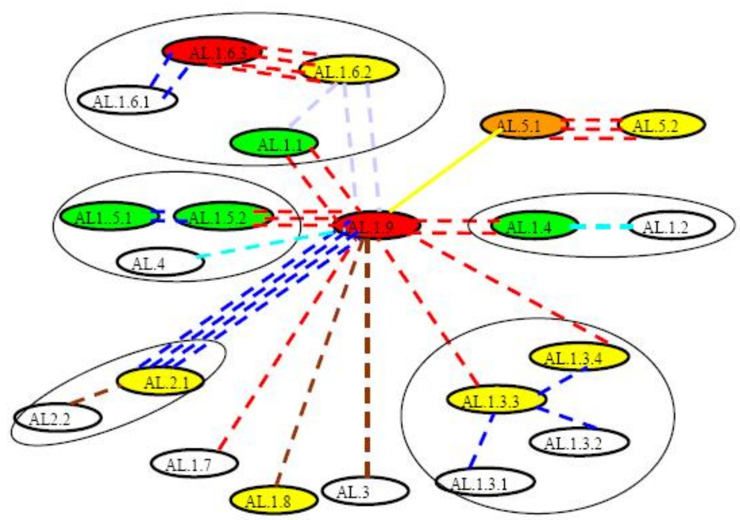


Figure 2.1 Node-link diagrams for a car engine [26]

2.3 Connectivity graph

A connectivity graph is a representation scheme that shows the interrelationships between components. The difference between the connectivity graphs and the node link diagrams is that the former group the specific relations between the entities with different color schemes and arrows. One such connectivity graph is illustrated on Figure 2.2 for a headlight module. In this case, the number of components is limited and hence the ability to visualize is relatively easy. However increasing the number of components significantly would make this graph as difficult to understand and interpret as a node-link diagram. As a result, a connectivity graph may also not be the best candidate for the modeling scheme researched here.



Key

Part #	AL.1.1	AL.1.2	AL.1.3	AL.1.3.1	AL.1.3.2	AL.1.3.3	AL.1.3.4	AL.1.4	AL.1.5	AL.1.5.1	AL.1.5.2	AL.1.6	AL.1.6.1	AL.1.6.2
Part Name	Vertical adjust motor	Static Light	Light Trim	Dynamic light trim ring	Static light trim ring	Light trim backing	Light trim base	Static light housing	Turn-light housing	Turn-light housing lens	Turn-light housing casing	Dynamic light sub-assembly	Dynamic light trim	Dynamic light bracket

Part #	AL.1.6.3	AL.1.7	AL.1.8	AL.1.9	AL.2	AL.2.1	AL.2.2	AL.3	AL.4	AL.5	AL.5.1	AL.5.2
Part Name	Dynamic light	Manual adjust bracket	Wiring harness	Headlight casing	Light access cover assembly	Light access cover	Light access cover seal	Vent Cover	Turn-Light Sub-assembly	Headlight lens sub-assembly	Headlight lens	Headlight lens trim

Figure 2.2 Connectivity graph (with key) for a headlamp [27]

2.4 Graphic Style Sheet

A node-link diagram can be transformed into the Graph Style Sheet (GSS) language by applying specific layout and styling rules to nodes. The central elements of the nodes are shown as icons. Figure 2.3 shows the GSS of airport data wherein persons (that form the central elements of the network) are enlarged. These style sheets enhance the understanding of the graph, making it easier for the user to interpret the information given without going to a lower level of representation [28]. One disadvantage of this type of representation is that it requires considerable space to represent the connectivity between the nodes. In addition, as the number of central elements or nodes increases, the representation becomes much more complicated. Also, as the number of central elements (nodes) increases, traceability between them may be difficult. Hence, this also is not the best candidate for the modeling scheme needed in this research.

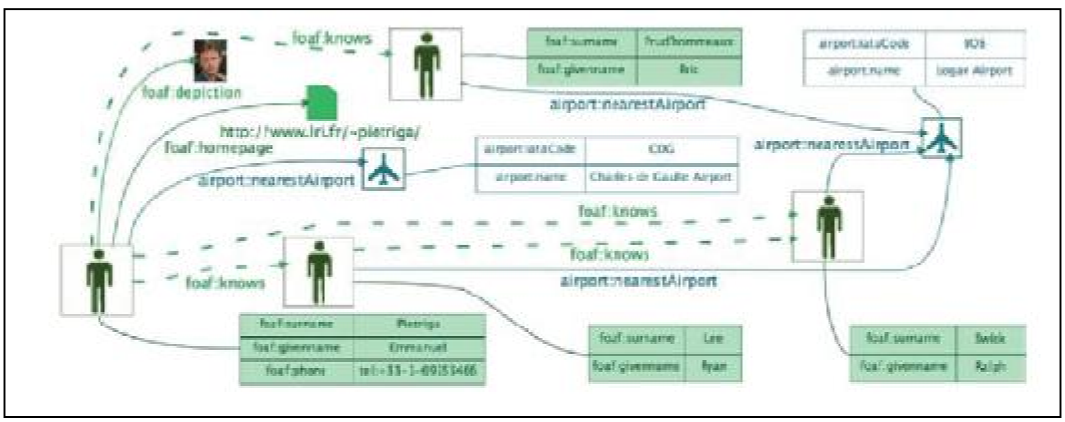


Figure 2.3 Graphic style sheet for airport data [28]

2.5 Treemapping

Tree maps are used to visualize the hierarchical representation of entities in a space-constrained environment. The properties of the leaf nodes are illustrated using different sizes and colors, enabling users to determine patterns by comparing these nodes and sub-trees, even at lower levels [29]. A typical representation of treemapping is shown in Figure 2.4. It shows the breakdown of the entities from a higher to a lower level, each representing various nodes of the Microsoft Windows operating system. Though the ability to spot patterns is advantageous, this representation scheme does not allow for the tracing of entities (nodes). As traceability is considered to be important for what-if scenarios in a complex system, this scheme is not considered to be the best option for the modeling scheme researched in this work.

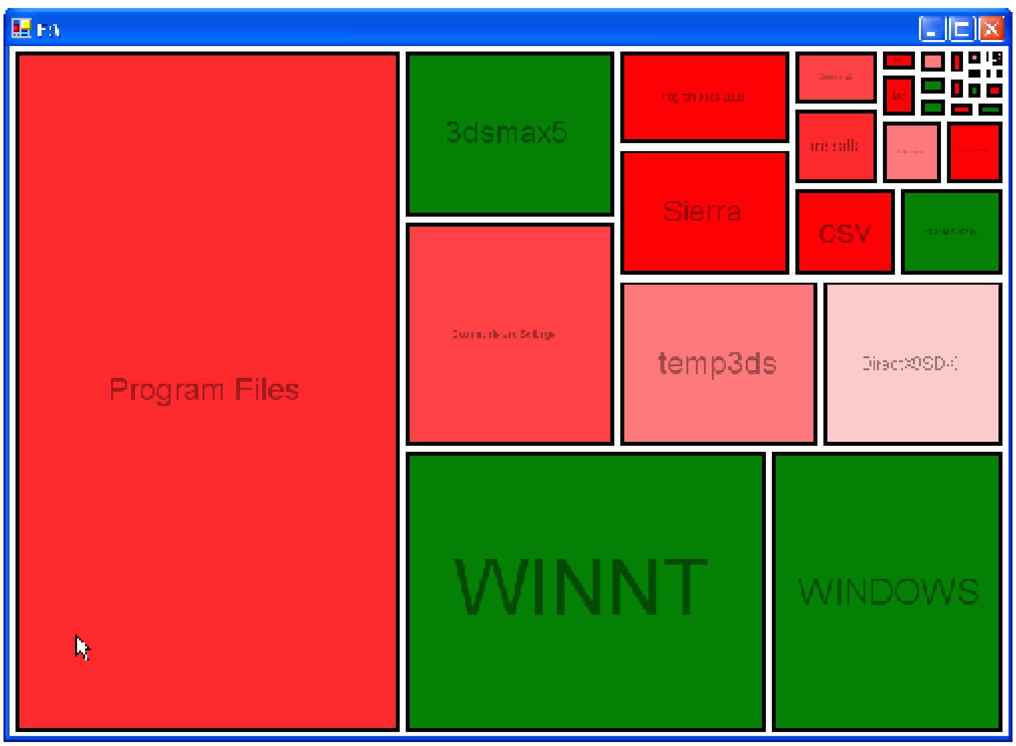


Figure 2.4 Tree mapping in a space-constrained environment [29]

2.6 Matrix Based Representation Schemes

In the field of engineering design, matrix-based representation is primarily used to establish a quantitative or a qualitative relationship between the entities in the row headers with those of the column headers of the matrix. While both relationships are valuable, the advantage of the quantitative matrix-based method is its ability to trace entities across a series of matrices thereby allowing the user to analyze what-if scenarios more efficiently. There are several methods and approaches that use the matrix-based representation schemes. Some of them are discussed briefly in the sub-sections below.

2.6.1 House of Quality

The House of Quality (HoQ), a tool comprehensively used by Quality Function Deployment (QFD) is an effective tool for modeling the complex interactions between the customer requirements and the engineering characteristics of an artifact. Shown below is a generic representation of a house of quality.

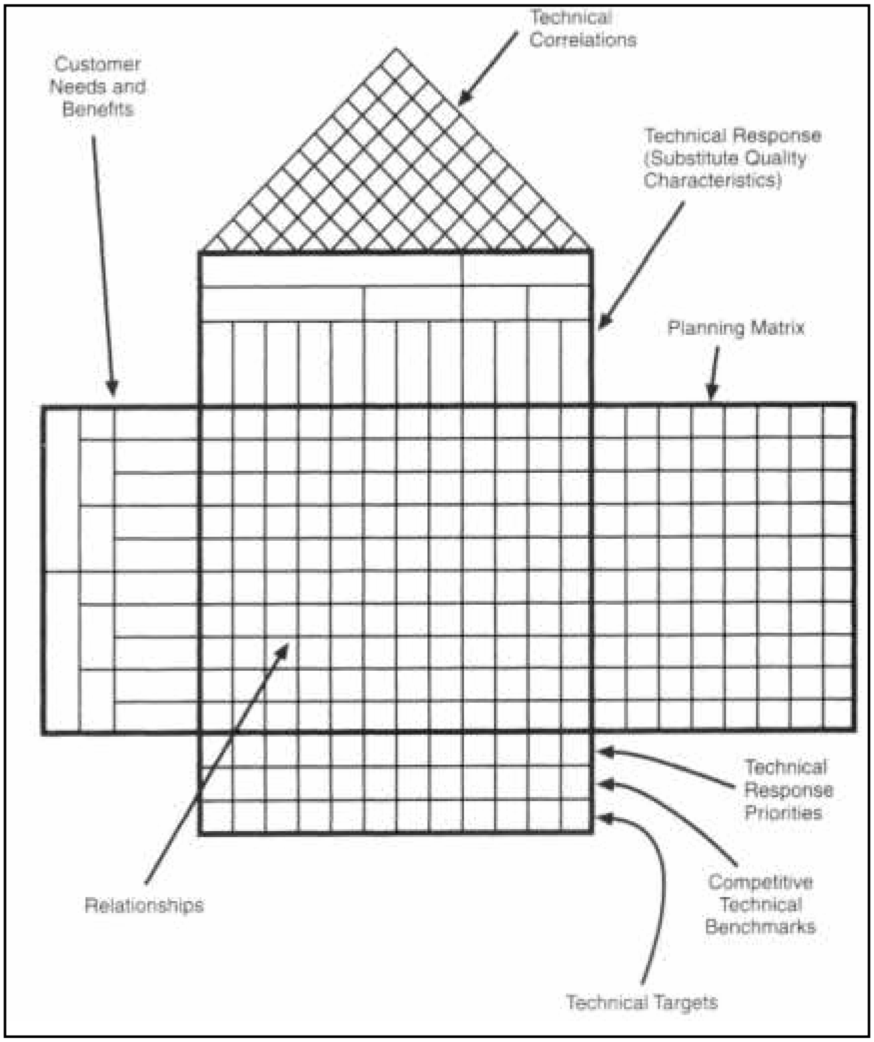


Figure 2.5 House of Quality [31]

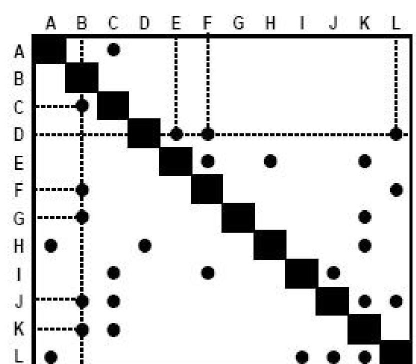
The customer requirements are captured in row headings of the HoQ in a hierarchical manner. The roof of the HoQ relates the technical correlations or engineering characteristics the designer can change to affect the design [30]. Quantitative (0-1; 9-3-1) or qualitative (different symbols) mapping schemes are used to correlate the customer requirements and engineering characteristics. Priorities, competitive benchmarks and targets form the bottom of the house (its foundation). The relationship module converts the “voice of the customer" (VOC) inputs into the more exacting, specific requirements as interpreted by the development team. HoQ can be used to compare the VOC inputs and the specific requirements to the characteristics of similar products, processes, or services found in the planning matrix. HoQ is an attention directing tool that enables design teams to focus attention on certain aspects by examining the row and column sums.

2.6.2 Design Structure Matrix (DSM)

A Design Structure Matrix (DSM), a compact, matrix representation of a system/project, is a representation and analysis tool for system modeling, especially for purposes of decomposition and integration [32]. DSM, a square matrix with identical row and column headings was developed to manage the sequence of design activities in the product development process. Cells in the matrix are populated with '1' or 'x' indicating a relationship between the corresponding row and column headers or '0' or ' ' if there is no relationship between them. Since, the entities in the row and column headers of the DSM are the same; the diagonal elements in the DSM always indicate a relation. Typical representations of a DSM are shown below in figure 2.6 (a) and 2.6 (b)

	A	B	C	D	E	F	G
A	1	1	0	1	0	0	0
B	0	1	0	1	0	0	1
C	1	0	1	0	1	1	0
D	0	0	0	1	1	0	0
E	1	1	0	0	1	0	1
F	0	0	1	1	0	1	0
G	0	1	0	0	1	1	1

(a)



(b)

Figure 2.6 Design Structure Matrices

The DSM displays the relationships between the entities of a system in a visual and analytically advantageous format. In Figure 2.6 (b) the directionality of the interactions is shown by placing the corresponding node to the left (feed forward) or right (feed backward).

2.6.3 Pugh Decision Matrix (PDM)

The Pugh Decision Matrix (PDM) primarily used as a concept selection tool, uses a scoring matrix called the Pugh Matrix. It is implemented by establishing an evaluation team and creating a matrix of evaluation criteria versus alternative concepts. This scoring matrix, usually associated with the QFD methodology, is a type of prioritization matrix. Usually, the options are scored relative to criteria using a symbolic representation with one symbol used for better than neutral, another for neutral, and another for worse than neutral. These are converted into scores and combined in the matrix to yield total scores for each option.

Criteria → ↓	Customer pain	Ease to solve	Effect on other systems	Speed to solve	Weighted Sum
Problems	5	2	1	2	
Customers wait for hose	High 3 x 5 = 15	Medium 2 x 2 = 4	High 3 x 1 =3	High 3 x 2 = 6	28
Customers wait for weather	Medium 2 x 5 = 10	Medium 2 x 2 = 4	Medium 2 x 1 = 2	Low 1 x 2 = 2	18
Customers wait for food	Medium 2 x 5 = 10	Low 1 x 2 = 2	Medium 2 x 1 = 2	Low 1 x 2 = 2	16
Customers wait for check	Low 1 x 5 = 5	Medium 2 x 2 = 4	Medium 2 x 1 = 2	Low 1 x 2 = 2	13

Figure 2.7 Pugh Decision matrix (PDM) [3]

2.6.4. Function Task Interaction Matrix (FTIM)

The Function-Task Interaction Matrix (FTIM) is a matrix-based method recently developed by Galvao and Sato [33] to relate the affordances between technical functions and user tasks. An affordance refers to a physical property of something that influences how it can be used. Technical functions and user tasks based respectively on functional modeling and task analysis are listed. FTIM relates technical functions (in row headings) and user processes (in column headings) and establishes the interactions between them. A typical representation of a Function Task Interaction matrix is shown in Figure 2.7.

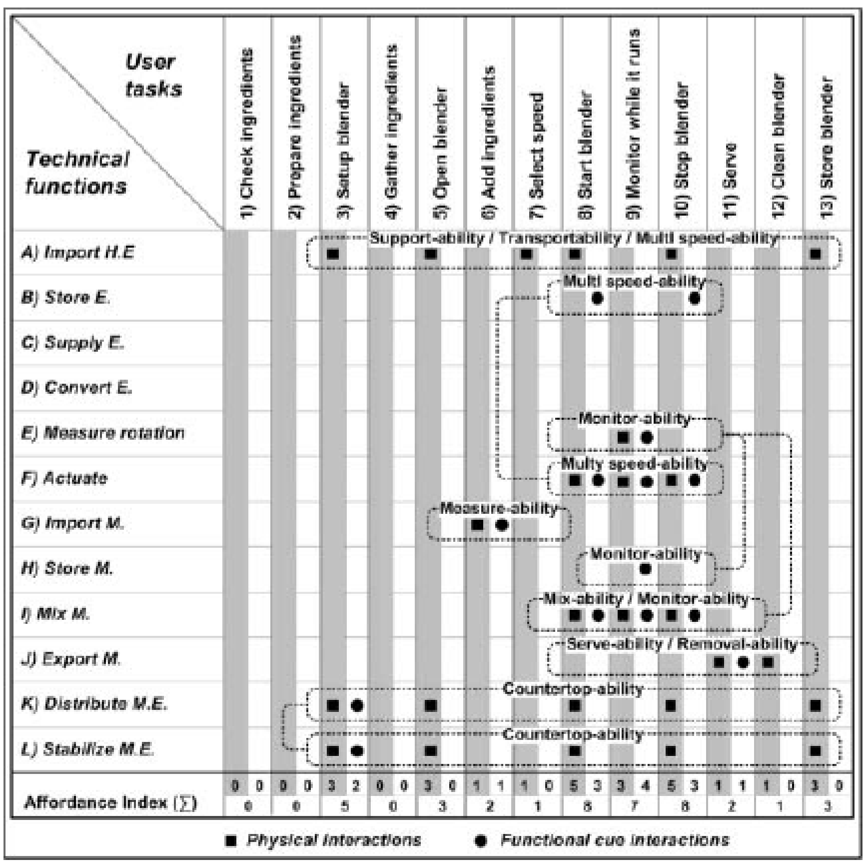


Figure 2.8 Function Task Interaction matrix adopted from Galvao et al., [33]

FTIM relates the functions and user processes by two types of interactions, namely the physical interactions and cognitive interactions. After the interactions are determined, they are summed, thereby denoting the affordance index.

2.6.5 Affordance Structure Matrix (ASM)

In recent work, Maier et al, have reported research into a matrix-based affordance structure matrix that maps the affordances to the artifact's structures. The Affordance Structure Matrix (ASM) serves as an attention directing and a concept exploration tool to compare the affordance-structure relationships across multiple artifacts [34]. A typical representation of an ASM is shown in Figure 2.8.

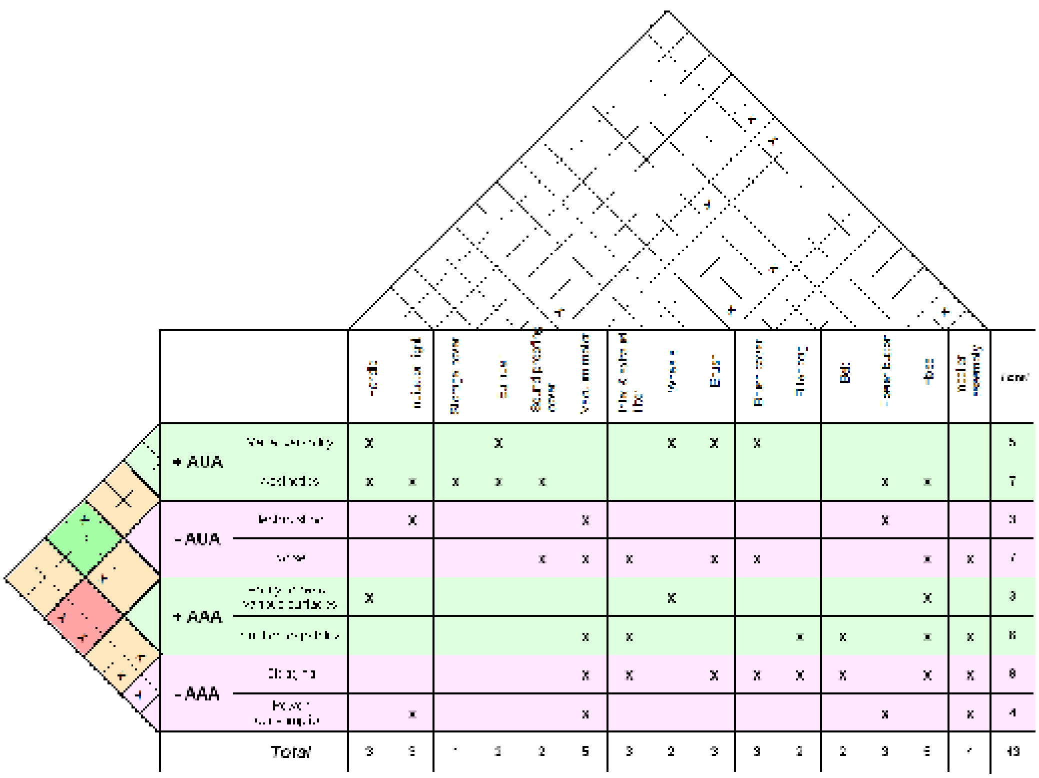


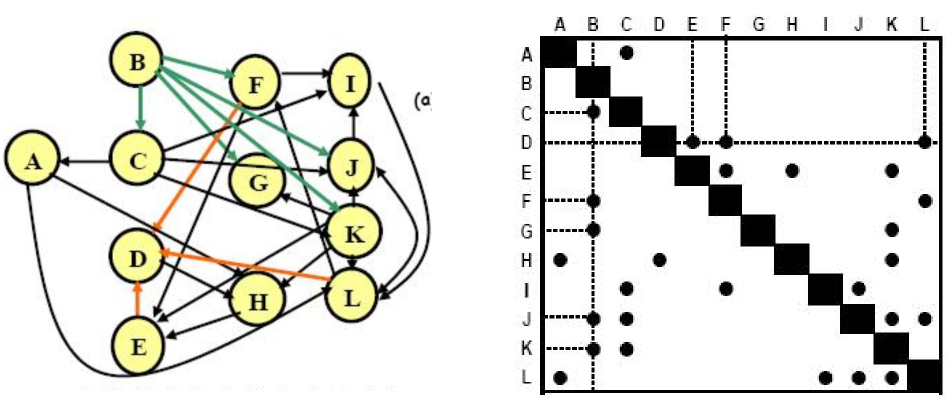
Figure 2.9 Affordance Structure Matrix for Bissell vacuum [34]

The ASM has a roof and a side to study the intra-domain relationships. The roof of the ASM represents a DSM style half-matrix. The side of the ASM represents the interactions between the affordances. Affordances are categorized into positive affordances, negative affordances, artifact-artifact affordances, artifact-user affordances. The totals on the right side and on the bottom of the ASM direct the designer's attention to important physical structures and affordances.

2.7 Advantages of Matrix Based Representation Schemes

2.7.1. Ease of interpretation

Figure 2.9 (a) represents the correlation of 12 entities using a connectivity graph and Figure 2.9 (b) represents the same in a DSM. It is apparent that the correlations in the connectivity graph overlap, which makes it difficult for the user to interpret the information. The same correlation is shown in a fairly structured way using a matrix based method as shown in Figure 2.9 (b). This makes the interpretation comparatively easier for the user.



(a) (b)

Figure 2.10 Representation of 12 entities using a connectivity graph and matrix-based approach [55]

2.7.2 Traceability

Another advantage of the matrix-based representations is their ability to allow tracking/traceability across various domains in different matrices. Consider three matrices as shown in Figure 2.10. If an entity, say C, is removed, then the entities related to C (BB, CC, DD) and (SS, UU) would be affected in the matrices 1 and 2, which in turn affects the entities in matrix 3 (AB, EF). Entities that would be affected if C is removed are shaded. On the other hand, traceability in a connectivity graph is much more complex as can be seen in Figure 2.11.

	A	B	C	D	E
AA	x				
BB	x	x	x		x
CC			x	x	
DD	x		x		
EE				x	

Matrix 1

	SS	TT	UU	VV
A	x			
B		x		x
C	x		x	
D	x	x		
E		x		x

Matrix 2

	AB	CD	EF
SS	x		x
TT		x	
UU	x		x
VV	x		x

Matrix 3

Figure 2.11 Traceability in a matrix-based representation

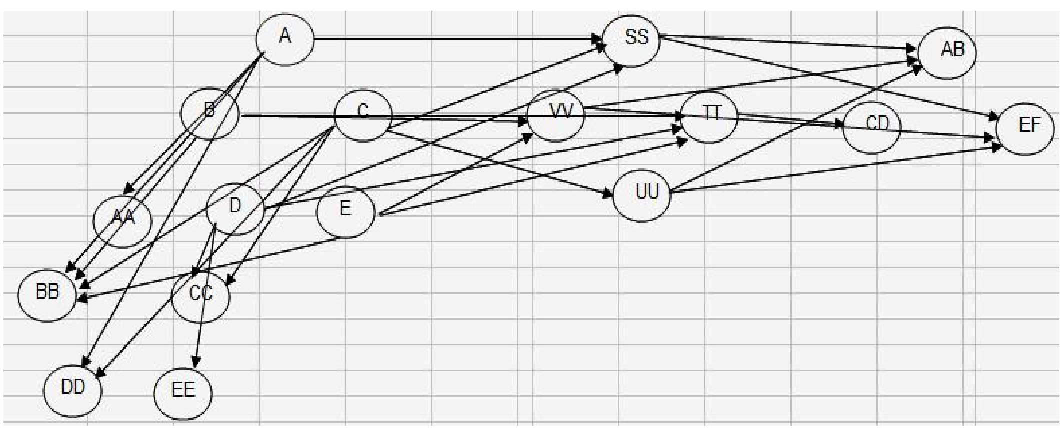


Figure 2.12 Traceability in a connectivity graph

2.7.3 Hierarchy

In figure 2.12, the domain “Voice of the company” has been listed in a hierarchical manner in the column headings of the HoQ. One can observe that the higher level entity in the domain “Enterprise product development capabilities” is divided into four sub-levels namely business capture, quality processes, project management and technology development. Each of these sub-levels is further divided into corresponding lower levels. Though hierarchy could be represented as a tree diagram, its ability to show more correlations with other entities using innumerous number of arrows makes it difficult to interpret. On the other hand, effective representation is achieved by using a matrix-based representation due to its capability to represent the correlation between large amounts of data in a comparatively smaller space, thereby providing a convenient user interface [26].

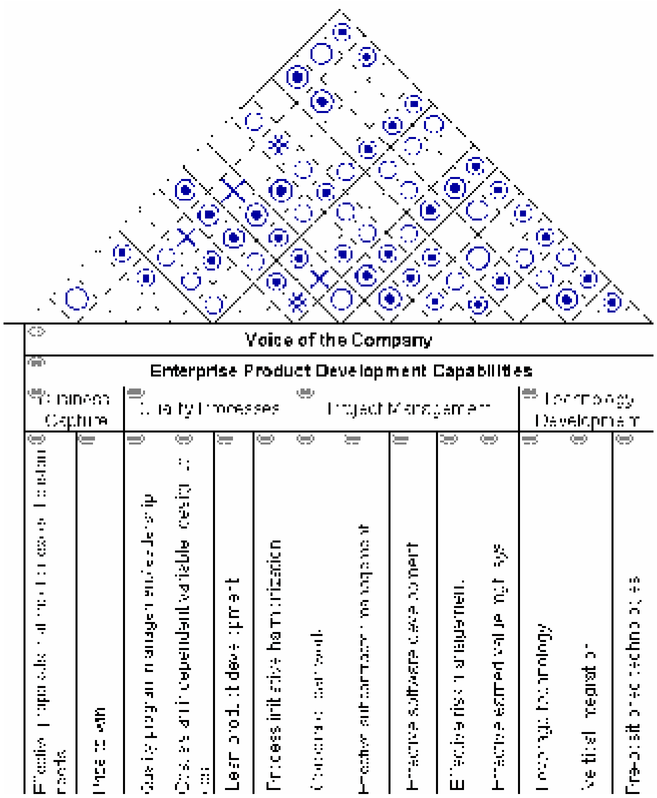


Figure 2.13 Hierarchy in HoQ [56]

When compared to other representation schemes, matrix-based representation schemes show relationships between large amounts of information fairly efficiently. The capability of the matrix-based methods to handle a larger space without causing much confusion in interpretation to users makes it a favorable representation scheme in engineering design. This information is supported by various researchers. Steward showed that matrix-based modeling approaches of engineering activities provide a means for both modeling and analyzing complex development process [32]. Ghoneim et al., conclude that the matrix representation scheme enables information and relationships to be quickly visualized when compared to the graph-based approaches [36]. Johansson and Krus (2006) argue that matrix-based modeling techniques provide an efficient way of displaying and interpreting relationships [37]. For these reasons, the matrix-based approach is used as the framework for the model developed. Development of the modeling scheme using matrix-based representation and the accompanying systematic method is discussed in the next chapter.

CHAPTER 3

DEVELOPMENT OF A MODELING SCHEME AND A SYSTEMATIC METHOD

3.1 Introduction

A comprehensive modeling scheme is needed to enable the designers to capture the domains of interest for their design and visualize how the information in each of these domains is related within and between each domain. Furthermore, the modeling scheme must allow the study of the effect of changing an entity in one domain, on the entities in that domain and on the entities in the other domains. Following the systematic engineering design methods, the need to model requirements, functions, working principles, components, and tests is identified. Two additional domains, controllable parameters and test measures have also been incorporated in the model. The framework of the modeling scheme and a systematic method to generate solutions to minimize mass are discussed in detail in this chapter. This modeling scheme and the method were developed as a group as a part of a requirements modeling project.

3.2 Framework of the Model

Considering the natural progression of the design process, the domains mentioned earlier are defined one after the other by the designers as follows: Requirements are defined, functions to fulfill those are selected based on some working principles, and next components are chosen to accomplish these functions.

Controllable parameters are selected and test measures and tests identified to validate the requirements. This order is the one we implemented in our framework. The first step in creating the model is to map the requirements to functions. Requirements form the row headings of the first matrix and functions form the column headings. A matrix is denoted by the domains involved in it. Therefore, the first matrix is called the requirements to functions matrix. The relationships between requirements and functions are then identified, and the mapping between the two is obtained by placing a 1 in a cell that is located at the intersection of a specific requirement and any function needed for it. To allow traceability, column heading of a matrix becomes the row heading of the succeeding matrix. This allows the user to analyze the effect of one domain over the other. For example, function, the domain that is listed in the column headings of the requirements to functions matrix, forms the row headings of the second matrix. Working principles are listed in the column headings of the second matrix. This matrix is called the functions to working principles matrix. Similarly, the third matrix becomes working principles to components matrix, with working principles in its row headings and components in its column headings. Likewise, component to controllable parameters matrix, controllable parameters to test measures matrix and test measures to tests matrix are populated and they form the fourth, fifth and sixth matrices of the modeling scheme respectively. These six matrices form the primary level of the matrix.

The matrices in the secondary to sixth level of the model are obtained in two ways. One by manually populating the matrix based on the knowledge and understanding, and the other is to automatically generate the matrix by multiplying the corresponding matrices at the primary level. For example, the functions to components matrix is obtained automatically by multiplying the functions to working principles matrix and the working principles to components matrix from the primary level. Using a quantitative relationship scheme to represent the relationship between the domains facilitates matrix multiplication and allows the formation of other levels in the model. Secondary level matrices are obtained by multiplying two consecutive matrices in the primary level. Tertiary level matrices are obtained by multiplying three consecutive matrices in the primary level. Similarly, all the matrices at a lower level of the model are generated automatically by matrix multiplication from the levels above. For example, the requirements to tests matrix, a sixth level matrix in the model, is obtained by multiplying six consecutive primary level matrices, namely, requirements to functions matrix, functions to working principles matrix, working principles to components matrix, components to controllable parameters matrix, controllable parameters to test measures matrix and test measures to test matrix. The different levels of the model are shown in the Figure 3.1.

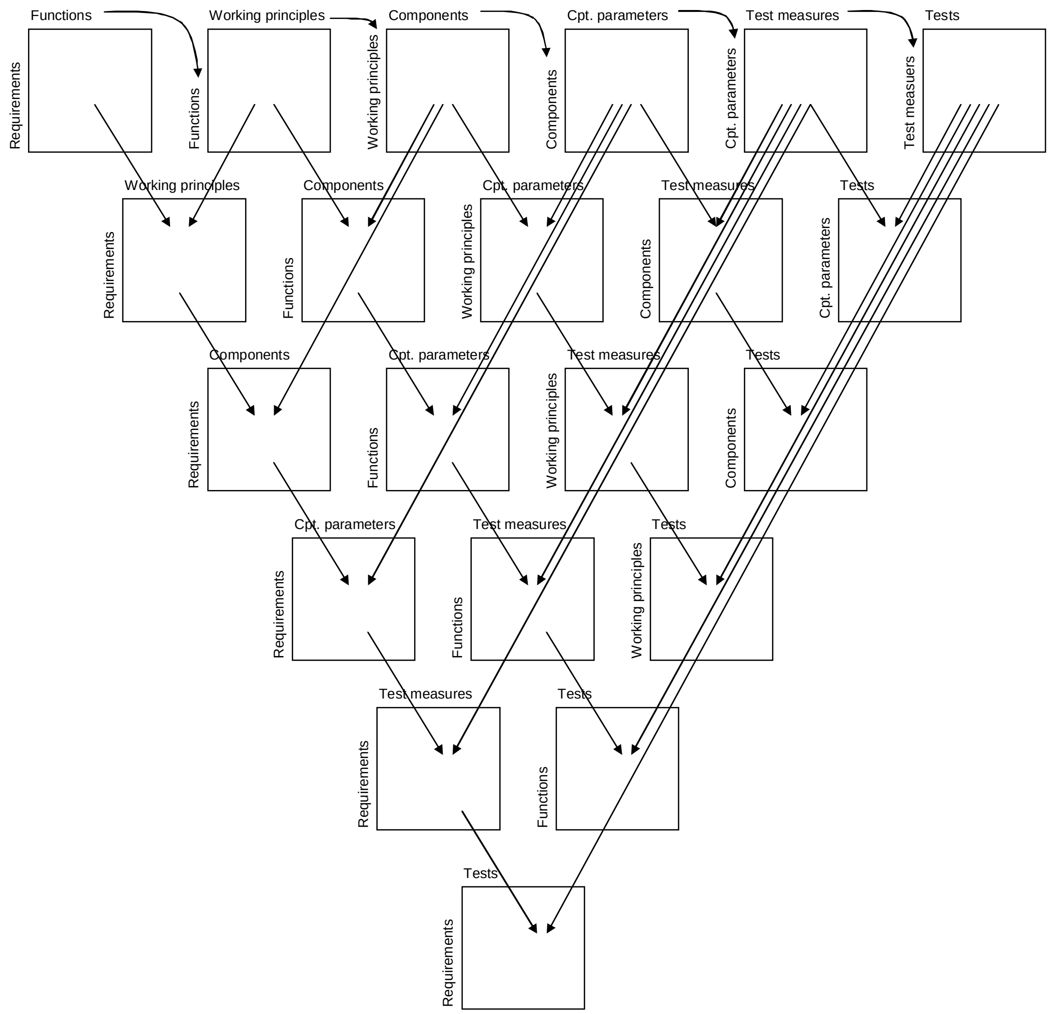


Figure 3.1 Model matrices capturing seven domains of interest

Having described how the various domains can be related we can now describe the methods we have built on top of this representation.

3.3. Systematic Method

The systematic method involves 5 major steps. They are:

1. Populating the primary level matrices.

2. Generating automatically the second to sixth level matrices and populating critical matrices at lower levels by hand.

3. Performing consistency checks to analyze and improve the consistency of the matrices in the secondary to sixth level and possibly correcting first level matrices.

4. Executing steps to find potential solutions that reduce the mass of the system

5. Conducting a feasibility study to find the feasible solution(s) (from the pool of generated solutions) for mass reduction that can be considered for further development.

Each of these steps is discussed in detail in the sub-sections given below.

3.3.1 Steps to Populate Primary Level Matrices of the Model

Several steps are needed to populate the primary level matrices correctly and consistently. Eliciting incorrect information may lead to incorrect observations at a later stage. First, it is advisable to exercise the method as a team. This reduces inconsistencies and results in a team effort that gives confidence in the observations or conclusions made for the system under investigation. Apart from domains, two important terminologies are used throughout the modeling scheme. They are entities and hierarchy.

Entity: An item in a domain is referred to as an entity. For example, thermostat and radiator are entities of the component domain. Maximum heat dissipated is an entity in the component parameter domain.

Hierarchy: Entities in the domains are listed with up to three levels of categorization. For example, entities in the function domain typically include a top level function (system level), mid-level function (sub-system or assembly level) and a lower level function (component level). A sample of the hierarchical representation of entities in the function domain is shown in Figure 3.2.

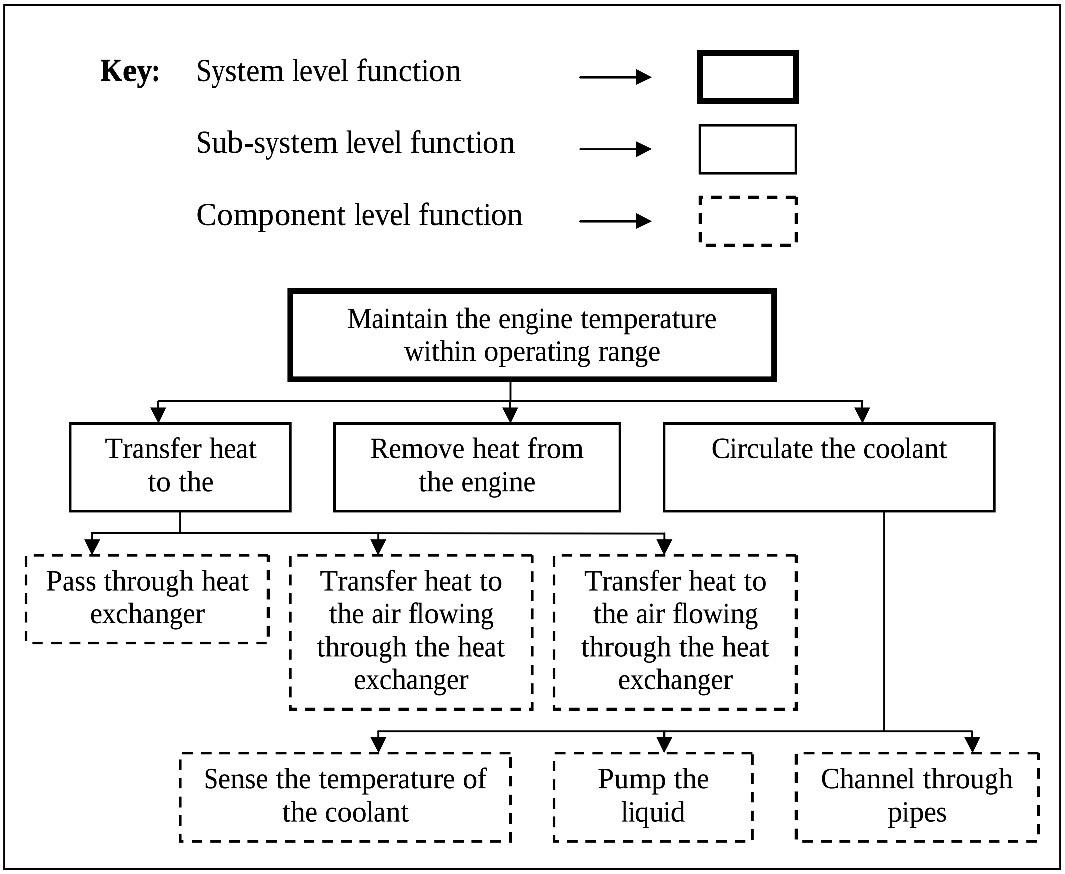


Figure 3.2 Functional Hierarchy

<u>3.3.1.1 Phase 0</u>

Before using the modeling scheme to fill the matrices, a phase 0 is required. This phase defines the system under investigation based on the flowchart shown in figure 3.3. The steps to be followed are in the middle, with the input on the left and output on the right.

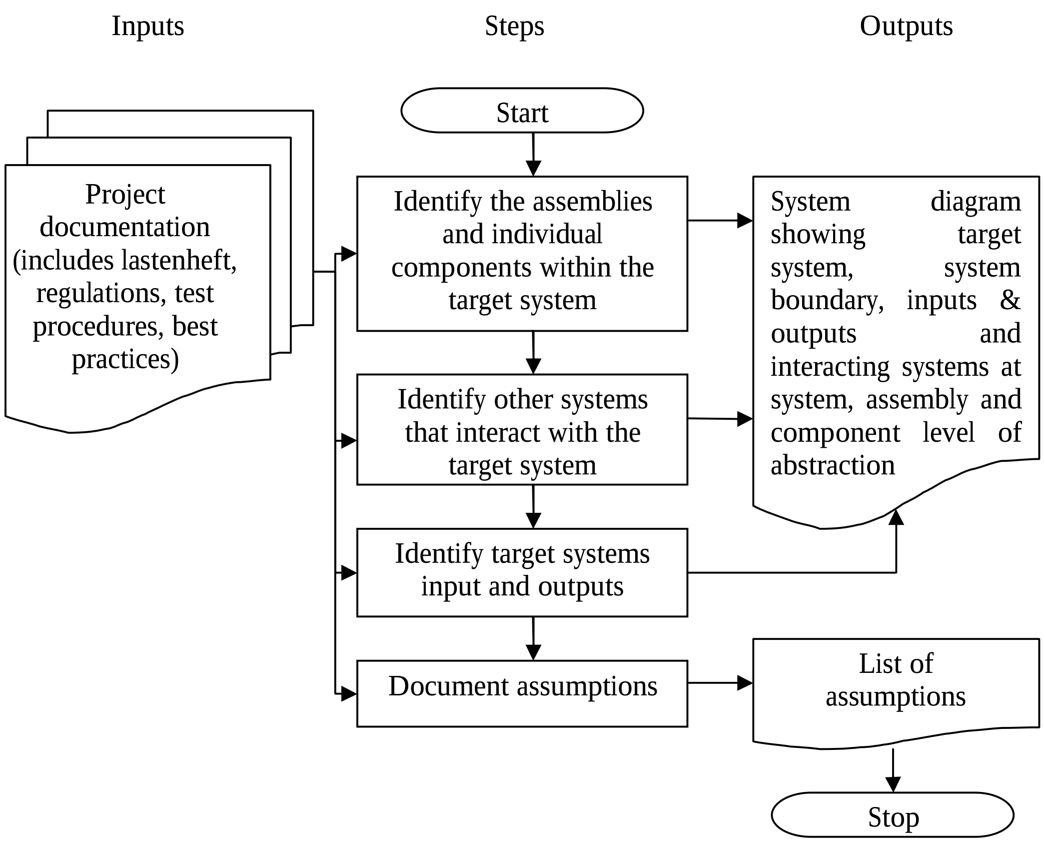


Figure 3.3 Flowchart for Phase 0

Input for this phase is the project documentation that includes the "*lastenheft*" or requirements list, regulations, test procedures, best practices, online resources and information gained from reliable resources with references provided as necessary.

1. After obtaining the project documentation, the system boundary is drawn. Denoted as target system, it is composed of entities such as assemblies, sub-assemblies / components.
2. After this boundary is identified, the other systems interacting with the target system are listed.
3. Next, the inputs and outputs of the target system and interfaces to other systems are defined. The medium (fluid, air) is listed for each type of interaction.

4. The output from these three steps are system diagrams showing the target system, the system boundary, the inputs and outputs and the interacting systems at a system level of abstraction.
5. Assumptions relevant to the target system are documented and the rationale for each is given. Output from this step is a list of assumptions.

   Executing these steps completes Phase 0.

3.3.1.2 Phase 1

Phase 1 involves the steps required to formulate the requirements to functions matrix as outlined in the flowchart shown in figure 3.4. For efficient calculation and analysis purposes, an Excel template that consists of empty modeling matrices in the primary level to sixth level has been developed and can be used to easily populate the matrices and accomplish the matrix multiplications. This matrix is available on the accompanying CD at the end of the thesis.

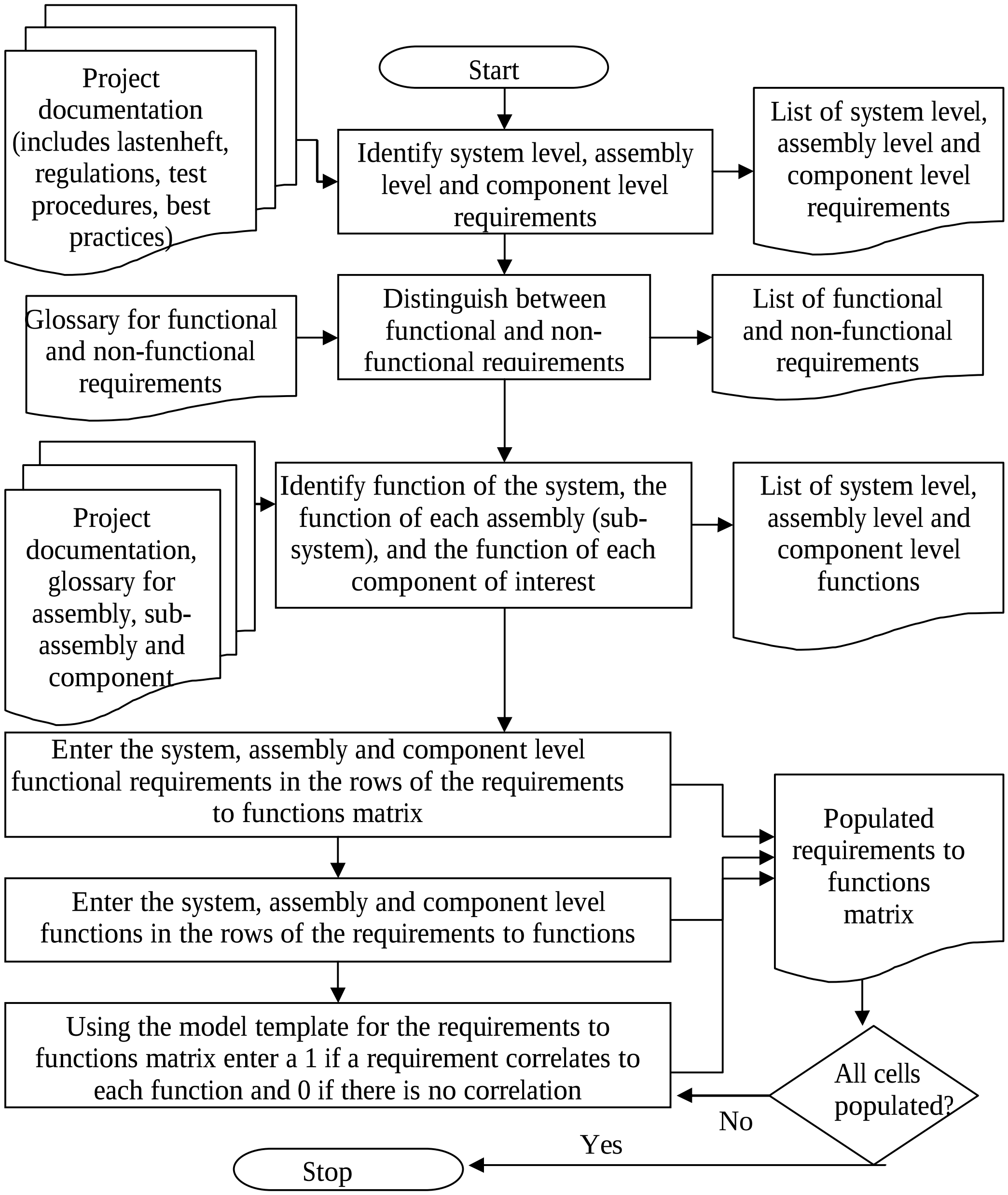


Figure 3.4 Flowchart for Phase 1

1. The requirements of the target system at the system, assembly and component levels are identified from the project documentation, including the *lastenheft,* regulations, test procedures, best practices, online resources and information gained from reliable resources with references provided as necessary. These requirements are identified and agreed upon by the team to ensure overall

agreement on the information gathered. The list of requirements is the output of this phase.

2. Next, the individual requirements are categorized as functional or non-functional. Otto and Wood [38] define functional requirement as “Statements of the specific performance of a design, that is, what the device should do. Functional requirements should be stated, initially, in the broadest (most generic) terms. They should focus on performance, be stated in terms of logical relationships, and be stated, initially, in ‘solution neutral’ terms.” Our interpretation is that, for instance, a requirement is functional if it is a requirement on the strength or performance of the system under loading or it is a requirement on the movement of the system or it is a requirement on conditions in which the system must operate or it is a requirement on the interaction between the system and the user. If a requirement obtained from step 1 satisfies these criteria, then it can be categorized as a functional requirement. A requirement is non-functional if it is a requirement only on the geometry of the system or it is a requirement on the styling or appearance of the system or it is a requirement on a specific material, or it is a requirement on environmental compliance such as recycling. If a requirement obtained from step 1 satisfies these criteria, then it can be categorized as a non-functional requirement. A final list of functional and non-functional requirements obtained by the mutual consent of the team members is the output of this step. The system, assembly and component level requirements are categorized and listed, forming the requirements hierarchy.

3. In this step, the functions for the system, assembly and component levels of the target system are identified based on the definition of ‘function’ in the glossaries included in the Appendix A. The system, assembly and the component level functions are listed, forming the function hierarchy.
4. The system, assembly and component level functional requirements are entered into the row headings of the model template of the requirements to functions matrix. The requirements at each level may be numbered to reflect their hierarchical interrelationship.
5. The system, assembly and component level functions are entered into the column headings of the model template of the requirements to functions matrix. Functions and requirements at each level could be numbered to reflect their hierarchical interrelationship similar to requirements.
6. After the requirements and functions are entered into the requirements to functions matrix, the matrix is populated. If there is any correlation between a requirement and a function, then a ‘1’ is entered in the matrix at the corresponding cell. If there is no correlation, a ‘0’ is entered. The user can refer to the project documentation while populating the matrices.

The outputs of phase 1 are the requirements hierarchy, the function hierarchy and a populated requirement to functions matrix.

3.3.1.3 Phase 2

Phase 2 involves the steps required to formulate the functions to working principles matrix as seen in the flowchart shown in figure 3.5.

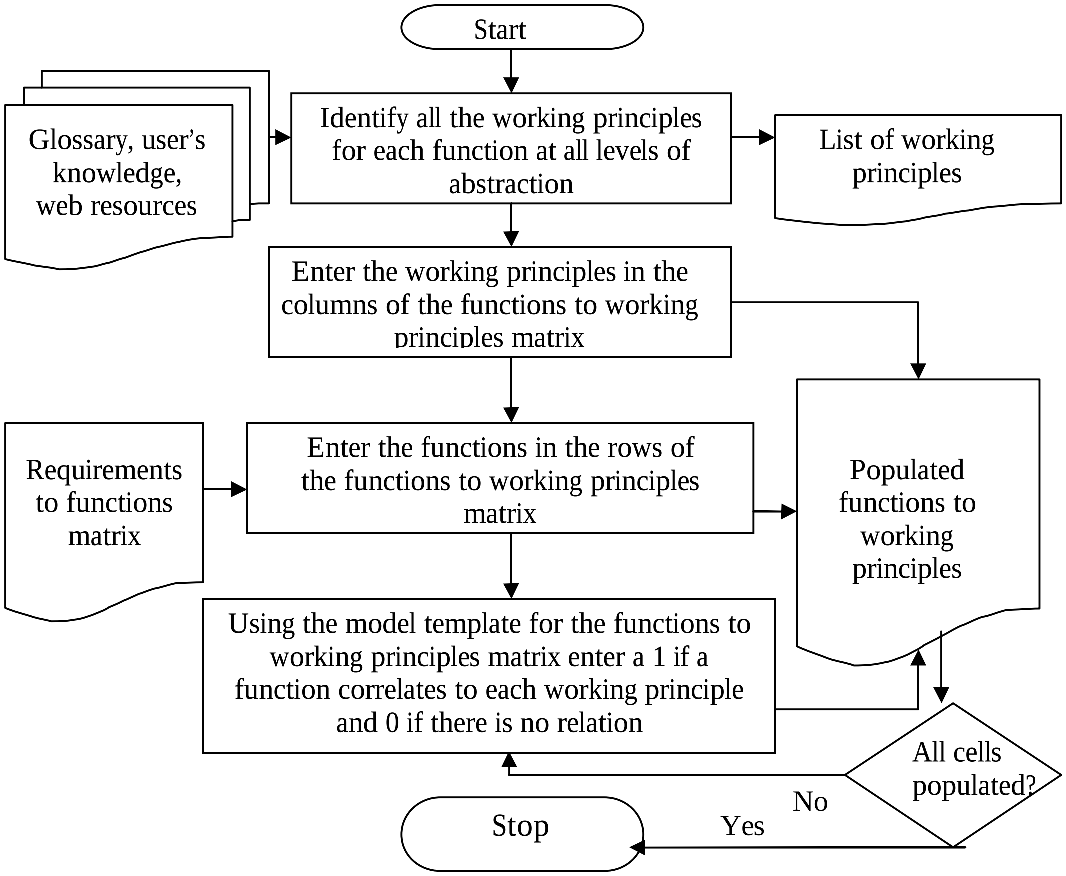


Figure 3.5 Flowchart for Phase 2

1. For every function at each level of the hierarchy, the working principles are listed by the mutual consent of the team.
2. The working principles are entered into the column headings of the functions to working principles matrix. Each working principle must be correlated with its appropriate function. This helps to analyze the diagonalization aspect in the matrix.
3. The functions from the requirements to function matrix form the row headings of the functions to working principles matrix.
4. After the functions and working principles are entered into the functions to working principles matrix, it is populated. If there is any correlation between a

function and a working principle, then a '1' is entered in the matrix at the corresponding cell. If there is no correlation, a 0 is entered. The user can refer to the project documentation while populating the matrices.

The outputs of phase 2 are the working principle list and a populated functions to working principles matrix.

3.3.4 Phase 3

Phase 3 involves the steps required to formulate the working principles to components matrix as seen in the flowchart shown in figure 3.6.

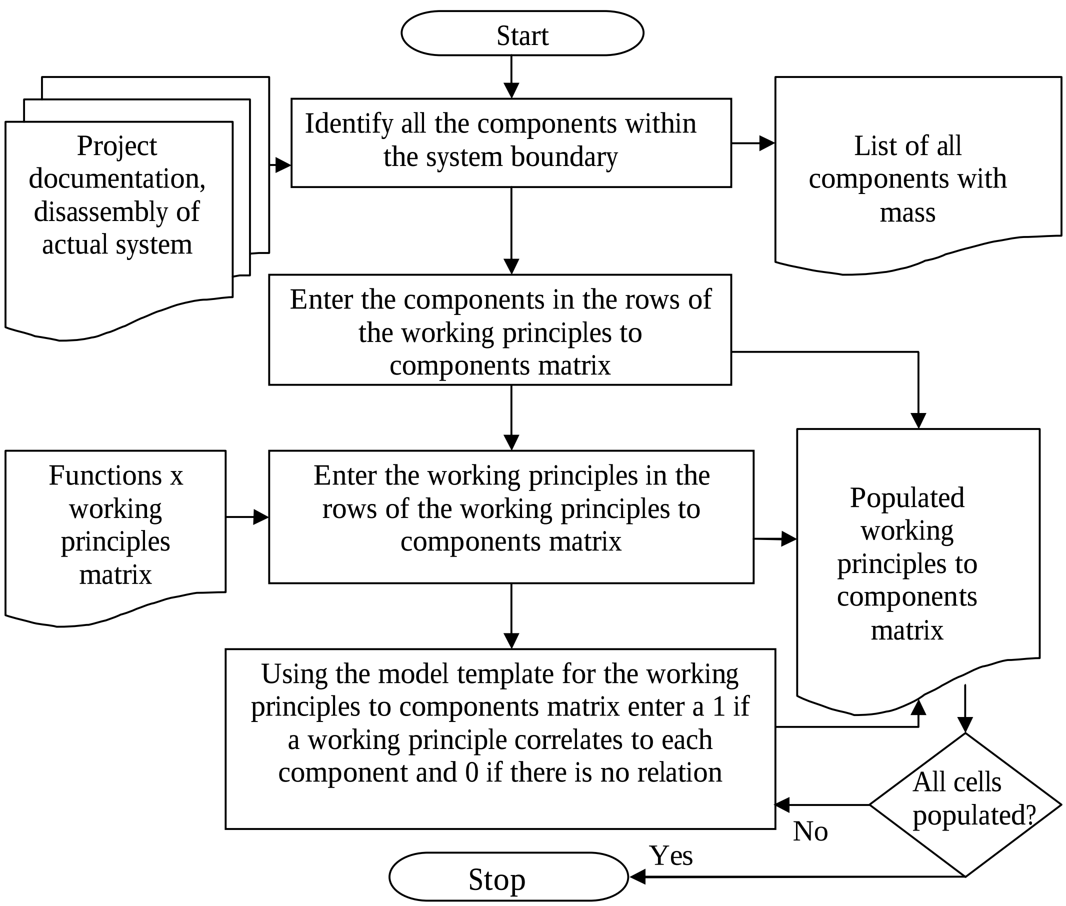


Figure 3.6 Flowchart for Phase 3

1. All the components in the system boundary (target system) are listed. Users can refer to project documentation and disassembly diagrams of the target system to form this list. For larger systems, having greater than 30 components, small items such as fasteners, bearings, seals etc.,) can be lumped together. It may also be sensible to omit some components such as trim pieces, wiring harnesses, etc. After the mutual consent of the team, the components list is finalized. The mass of the components is also listed along with the component list.
2. The refined list of components from the previous step is entered into the column headings of the working principles to components matrix. Each component must be correlated with its corresponding working principle.
3. The working principles from the function to working principles matrix form the row headings of the working principle to components matrix.
4. After the working principles and components are entered into the working principle to components matrix, it is populated. If there is any correlation between a working principle and a component, then a '1' is entered in the matrix at the corresponding cell. If there is no correlation, a '0' is entered.

The output of phase 3 is a finalized list of components in the target system and a populated working principle to components matrix.

3.3.1.5 Phase 4

Phase 4 involves the steps required to formulate the component to controllable parameters matrix as shown in Figure 3.7.

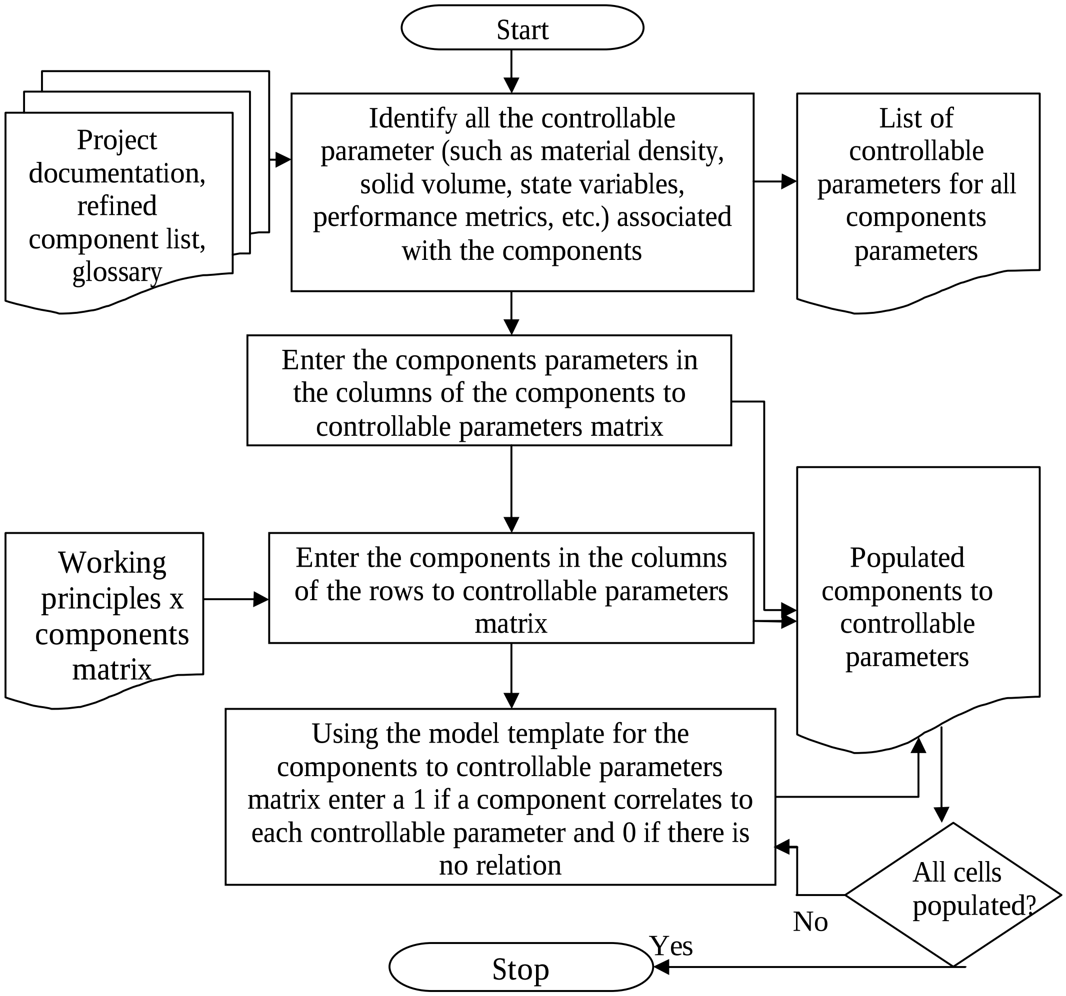


Figure 3.7 Flowchart for Phase 4

1. Controllable parameters are those parameters that the designer has control over while designing or re-designing an artifact. Controllable parameters include material density, solid volume, state variables, performance metrics, etc. Controllable parameters are identified for the assembly, sub-assembly and components and listed. The choice of controllable parameters is subjective, but need not be exhaustive. For example, the designer has control over the radius of a fillet, but changing that parameter will lead to only a negligible effect on the mass. However, changing the radius of a shaft or the thickness of sheet metal can

have a significant effect on the mass. By mutual consent of the team, the controllable parameters list is finalized. Output of this step is the list of relevant controllable parameters for the component list.

2. The refined list of controllable parameters from the previous step is entered into the column headings of the components to controllable parameters matrix. Each component must be correlated with its controllable parameters.
3. The components from the working principles to components matrix form the row headings of the components to the controllable parameters matrix.
4. After the components and controllable parameters are entered into the column and row headings of the components to controllable parameters matrix, it is populated. If there is any correlation between a component and a component, then a '1' is entered in the matrix at the corresponding cell. If there is no correlation, a '0' is entered.

The output of phase 4 is the finalized controllable parameters list of the components and populated components to controllable parameters matrix.

3.3.1.6 Phase 5

Phase 5 involves the steps required to formulate the test measures to tests matrix as shown in the flowchart shown in figure 3.8.

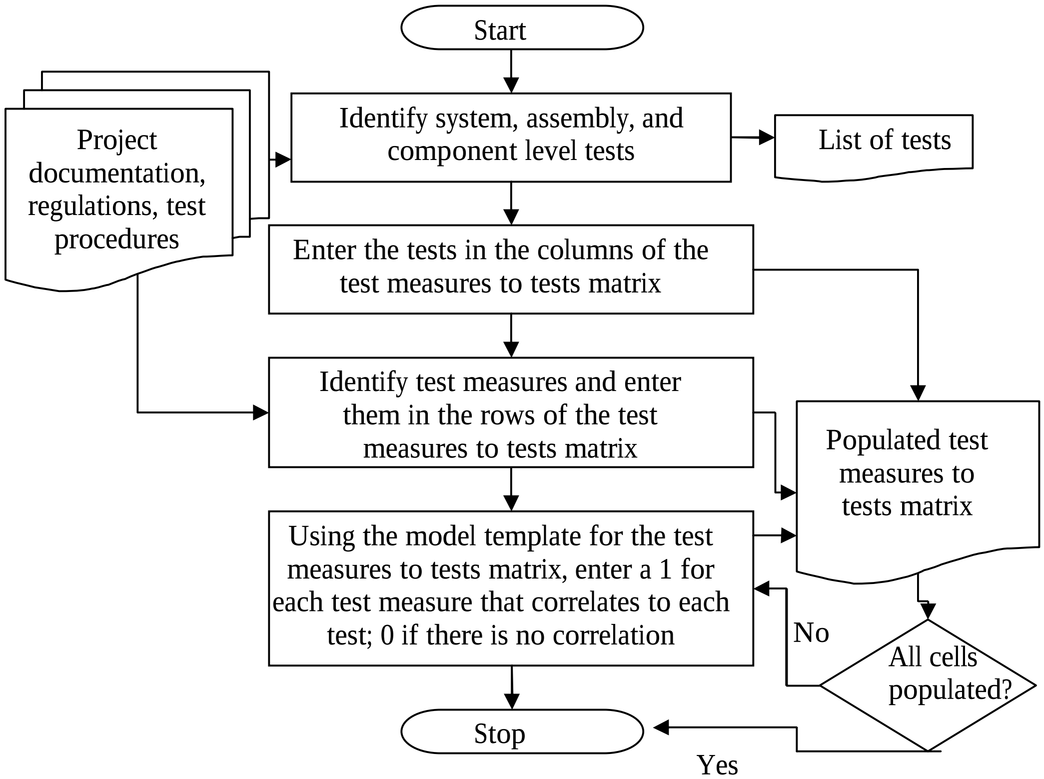


Figure 3.8 Flowchart for Phase 5

1. The system, assembly and component level tests that are required to verify if the requirements are satisfied are listed. The user can refer to project documentation and test procedures in order to list the tests. If a standard test is not available for a particular test measure, then the test is manually generated. For example, it may be necessary to consider the safety and reliability aspect while designing or re-designing an artifact. If a specific test associated with the safety and the reliability is not found in the project documentation, then user safety and reliability test is added to the list. By mutual consent of the team, the tests are finalized. The output of this step is the list of tests for the target system.

2. For every test, associated test measures are listed. By mutual consent of the team, the test measures list is finalized. Output of this step is the list of relevant test measures for the test list.
3. The refined list of test measures from the previous step is entered into the row headings of the test measures to tests matrix.
4. The finalized list of tests from step1 is entered into the column headings of the test measures to tests matrix. Each test must be correlated with its test measure
5. After the test measures and tests are entered into the row headings of the test measures to test matrix, it is populated. If there is any correlation between a test measure and a test, then a '1' is entered in the matrix at the corresponding cell. If there is no correlation, a 0 is entered.

The output of phase 5 is a list of relevant tests for each test measure and a populated test measure to tests matrix.

3.3.1.7 Phase 6

Phase 6 involves the steps required to formulate the controllable parameters to test measures matrix as shown in the flowchart below.

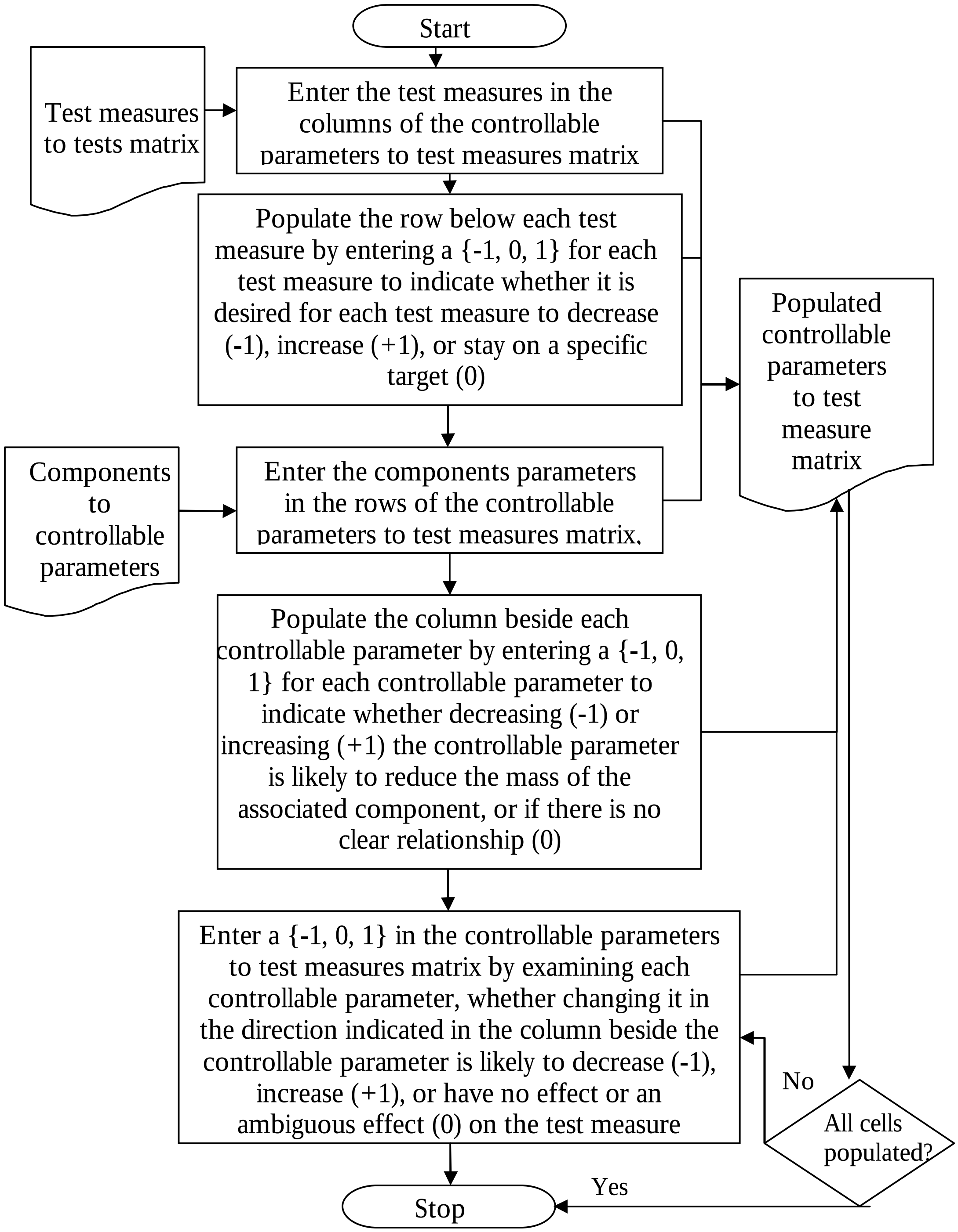


Figure 3.9 Flowchart for Phase 6

1. The controllable parameters from the components to controllable parameters matrix form the row headings of the controllable parameters to test measures matrix.
2. The test measures from the test measures to tests matrix form the column headings of the controllable parameters to test measures matrix.
3. Populate the row below each test measure by asking “if each controllable parameter is changed in the direction indicated (in the first column) to reduce mass, what will be the effect on each test measure?” Enter a ‘+1” at the corresponding cell if the indicated change in the controllable parameter will have a positive effect on the test measure. Enter a ‘-1’ if the indicated change in the controllable parameter will have a negative effect on the test measure. Enter a ‘0’ if the indicated change in the controllable parameter will have no effect on the test measure, or if the effect is not clear.
4. The controllable parameters from the components to controllable parameters matrix form the row headings of the controllable parameters to test measures matrix.
5. Populate the column beside each controllable parameter by entering a {-1, 0, 1} for each controllable parameter to indicate whether decreasing (-1) or increasing (+1) the controllable parameter is likely to reduce the mass of the associated component, or if there is no clear relationship (0).
6. After the controllable parameters and test measures are entered into the controllable parameters to test measures matrix, it is populated. If changing the controllable parameter in the direction indicated in the column beside it increases the effect on the test measure, then a ‘+1’ is entered at the corresponding cell. If

changing the controllable parameter in the direction indicated in the column beside it decreases the effect on the test measure, then a '-1' is entered. '0' is entered in the matrix if changing the controllable parameter in the direction indicated in the column beside it has no effect on the test measure.

The output of phase 6 is a finalized test measures list and populated controllable parameters to test measures matrix.

These seven phases (phase 0 – phase 6) are used to populate the primary level matrices in the model. It is necessary to analyze and improve the consistency of the matrices before executing the steps to generate solutions. This aspect is discussed in the next sub-section.

3.3.2 Steps to Analyze and Improve the Consistency of the Matrices

An Excel template that supports the modeling matrices has been programmed in a way such that the matrices in the secondary to the sixth level in the modeling scheme are automatically generated by matrix multiplication from the information entered in the primary level matrices. The automatically generated matrices in the secondary to sixth level should reflect similar correlations (0, 1) to those that would be obtained by manually populating each matrix. Inconsistencies may be due to errors in populating the matrices. Since two ways to generate the higher level matrices are available, it is necessary to analyze and improve the consistency of the matrices in the model before executing the steps that are used to generate solutions. This is accomplished by performing consistency checks. A consistency check analyzes the variation between the automatically generated matrix and the manually populated matrix. Four cases occur:

Cells can show a correlation in both the automatically generated matrix and the manually populated matrix. We refer to this case as “true positives”. This is the best scenario, we saw a relationship between two entities and multiplying lower level matrices confirmed that relationship.

The second case is if cells do not show a correlation in both the automatically generated matrix and the manually populated matrix. We call this case “true negatives”. If the cells show a correlation in the automatically generated matrix but do not show a correlation in the manually populated matrix, we have an inconsistency. We call this “false positives”. And finally, if cells show a correlation in the manually populated matrix but do not show a correlation in the automatically generated matrix, we have “false negatives”. The sum of true positives and true negatives divided by the total number of cells is the consistency metric. It gives a measure of how consistently we have populated the matrices. The sum of false positives and false negatives divided by the total number of cells is the inconsistency metric.

It is better to have 100% consistency. If not, the corresponding matrices must be checked again to ensure consistency. In order to perform the consistency check, the following steps have to be followed.

1. The secondary to sixth level matrices are manually populated.
2. False positives are examined to see if real relationships were missed in the manually populated matrix. False negatives are examined to see if real relationships were missed in higher level matrices. The manually populated matrices are revised as appropriate.

Executing these steps confirms the consistency of the matrices in the modeling scheme. Therefore, steps to find potential solutions to reduce mass can be executed. These are discussed in the next sub-section.

3.3.3 Steps to Find Potential Solutions to Reduce the System Mass

In order to generate solutions for minimizing mass, a sequence of steps discussed in this sub-section is necessary. These steps should be executed as a group to increase the likelihood of identifying solutions.

1. Identify solutions to reduce mass by removing non-functional requirements
    a. Using the existing Requirements to Functions matrix, consider the impact of removing or modifying each non-functional requirement.
    b. Identify possible component alterations to reduce mass that are constrained by non-functional requirements.
2. Identify solutions to reduce mass by using alternate components embodying existing working principles
    a. Using the mass list, identify components with significant mass.
    b. Using the existing working principles to components matrix, identify and list alternate lighter components for the components with significant mass that embody existing working principles.
    c. The mass of the alternate components embodying existing working principles is estimated and listed.
3. Identify solutions to reduce mass by using alternate working principles

   a. Using the existing functions to working principles matrix, alternate working principles for each existing working principle are identified and listed.
   b. Using the existing working principles to components matrix, alternate lighter components embodying each alternate working principle are identified and listed.
   c. The mass of alternate components embodying existing working principles are estimated and listed.
4. Identify solutions to reduce mass by eliminating high mass, low function components
   a. Components with significant mass are identified using the mass list and listed.
   b. Components that exhibit low functionality are identified using the function to component matrix and listed.
   c. Using the components to test measures matrix, components that do not have a negative impact on test measures are identified. These components that have low functionality can be eliminated.
5. Identify solutions to reduce mass by eliminating components that satisfy requirements that can be eliminated.
   a. Requirements that are no longer needed are identified and listed.
   b. Components that are only correlated to requirements that are no longer needed are identified and listed using the requirements to components matrix.

6. Identify solutions to reduce mass by eliminating components that satisfy functions that can be eliminated
    a. Functions that are no longer needed are identified and listed.
    b. Components that map to functions that are no longer needed are identified and listed using the functions to component matrix.
7. Identify solutions to reduce mass by optimizing controllable parameters
    a. Components with significant mass are identified and listed using the mass list.
    b. Single components parameters (of components with significant mass) to change to reduce mass without negatively affecting test measures are identified and listed using the controllable parameters to test measures matrix.
    c. Groups of components parameters (of components with significant mass) that can be changed to reduce mass and which have an overall net benefit or no negative effect on test measures are identified and listed using the controllable parameters to test measures matrix.

These 7 steps aid the designer to generate solutions to reduce mass. The steps to analyze the feasibility of the solutions and their combinations generated using these 7 steps are discussed in the next sub-section.

3.3.4 Feasibility Study and Combination of Solutions

Executing the steps in the previous section generates a pool of solutions that reduce the system's mass. But, all the solutions may not be feasible. In order to sort out the feasible solutions from the pool of solutions, a feasibility study is performed and a combination of solutions is analyzed for further consideration. To do that, the following steps are executed.

1. Each solution is analyzed for feasibility. The output of this step is a list of feasible solutions.
2. The feasible solutions are analyzed for expected mass reduction. The output of this step is the result of the expected mass reduction that accompanies each feasible solution.
3. The potential combinations of solutions for further development are selected based on feasibility, expected mass reduction, difficulty of implementation, effects on requirements, and effects on test measures.

Executing the sequence of steps in the sections 3.3.1 to 3.3.4 completes the method. In order to test the proposed method, a case study on a BMW Z4 cooling system is carried out. This case study is discussed in detail in the next chapter.

CHAPTER 4

CASE STUDY – BMW Z4 COOLING SYSTEM

4.1 Introduction

To validate the systematic method discussed in the previous chapter and to verify that it is capable of generating solutions for minimizing mass, it is applied to a BMW Z4 cooling system. The cooling system in an automobile is used to remove a part of the heat generated in the engine and keeping the later at its operating conditions. Maintaining the engine temperature is important to vaporize the fuel completely, to provide better combustion and to reduce emissions, to make the engine parts move more freely and to prevent metal parts wear. There are two types of automotive cooling systems: liquid-cooled and air-cooled. The BMW Z4 cooling system is a liquid-cooled one in which a liquid (coolant) is circulated through the engine block, thereby absorbing heat and cooling the engine. After the fluid leaves the engine, it passes through a heat exchanger (radiator) where heat transfer from the coolant to the air blowing through the heat exchanger takes place. A schematic representation of a cooling system is shown in Figure 4.1.

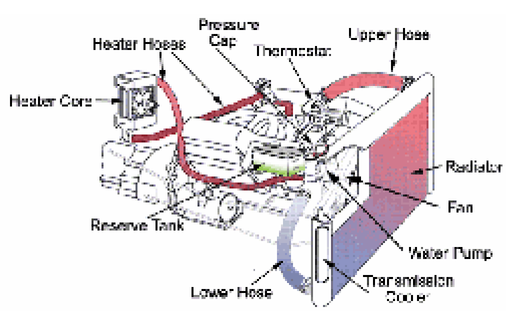


Figure 4.1 Cooling System of an Automobile [39]

4.2. Executing the Systematic Method

The 5 major steps in the systematic method are executed in order.

4.2.1 Populating the Primary Level Matrices

Initially the primary level matrices are populated. First, the primary level matrices are populated, then verified and modified by the team. This process resolved inconsistencies thereby affording confidence in the observations and conclusions made for the cooling system. For efficient calculation and analysis purposes, an Excel template is used to populate the primary level matrices.

4.2.1.1. Phase 0

Inputs for this phase include

- The BMW requirements list and test procedures from the *"lastenheft" or* requirements document.
- The existing physical system information provided by the vehicle technology representative from BMW.
- The generic cooling system requirements collected from outside literature / internet sources [40, 41, 42, 43].
- Exploded drawings of the cooling system found on the internet [44].

After obtaining the project documentation, the system boundary is drawn. Denoted as the target system, it is composed of assemblies, sub-assemblies and components of the cooling system along with a few entities from interacting systems specifically the air transport assembly, the transmission oil transport assembly, the refrigerant transport assembly and the engine assemblies. On the other hand the engine block, the heater fan, the compressor, the expansion valve, the electronic control unit and the battery that power the cooling system motor are not included in the system boundary. A schematic representation of the system boundary and an overview of the components of the target system are shown in Figure 4.2. After this boundary is identified, it is confirmed and finalized by the team.

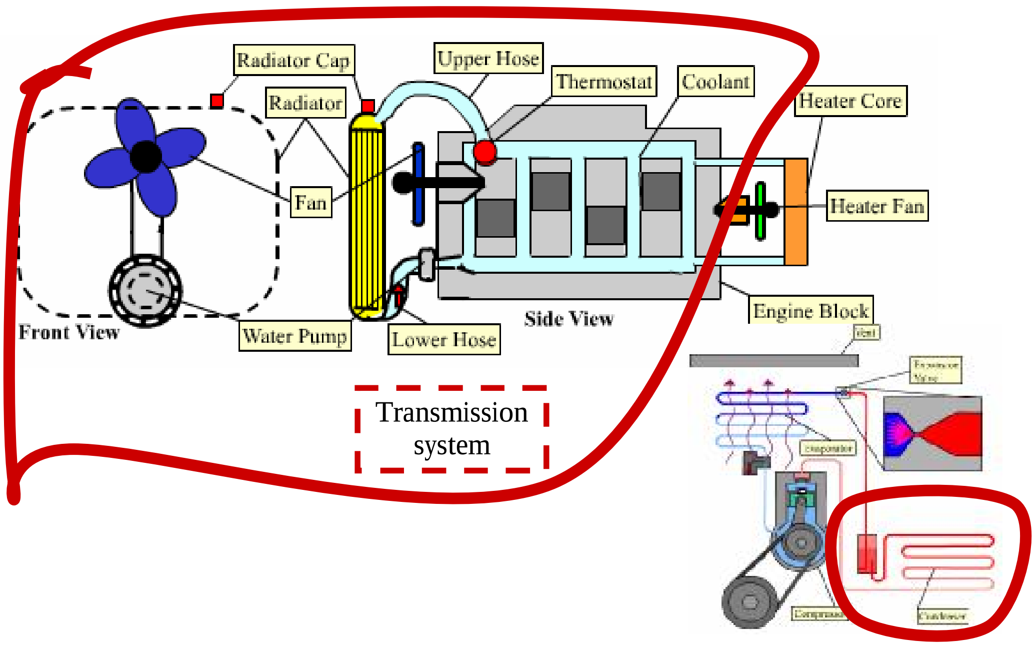


Figure 4.2 Cooling System and the System Boundary [52]

Next, the inputs and outputs of the target system and the interfaces with other systems are defined. For example, the inputs of the cooling system are air, coolant, transmission oil and refrigerant. As these mediums are channeled continuously through different assemblies in the target system, the input and output remain the same. The system diagrams showing the system boundary, the inputs and outputs and the interacting systems at the system, assembly and component level of the target system are shown in Figures 4.3, 4.4 and 4.5 respectively. The interacting mediums are denoted with different representations. The system diagrams are drawn at varying levels of abstraction to get a deeper understanding of the system and its interaction with the related ones.

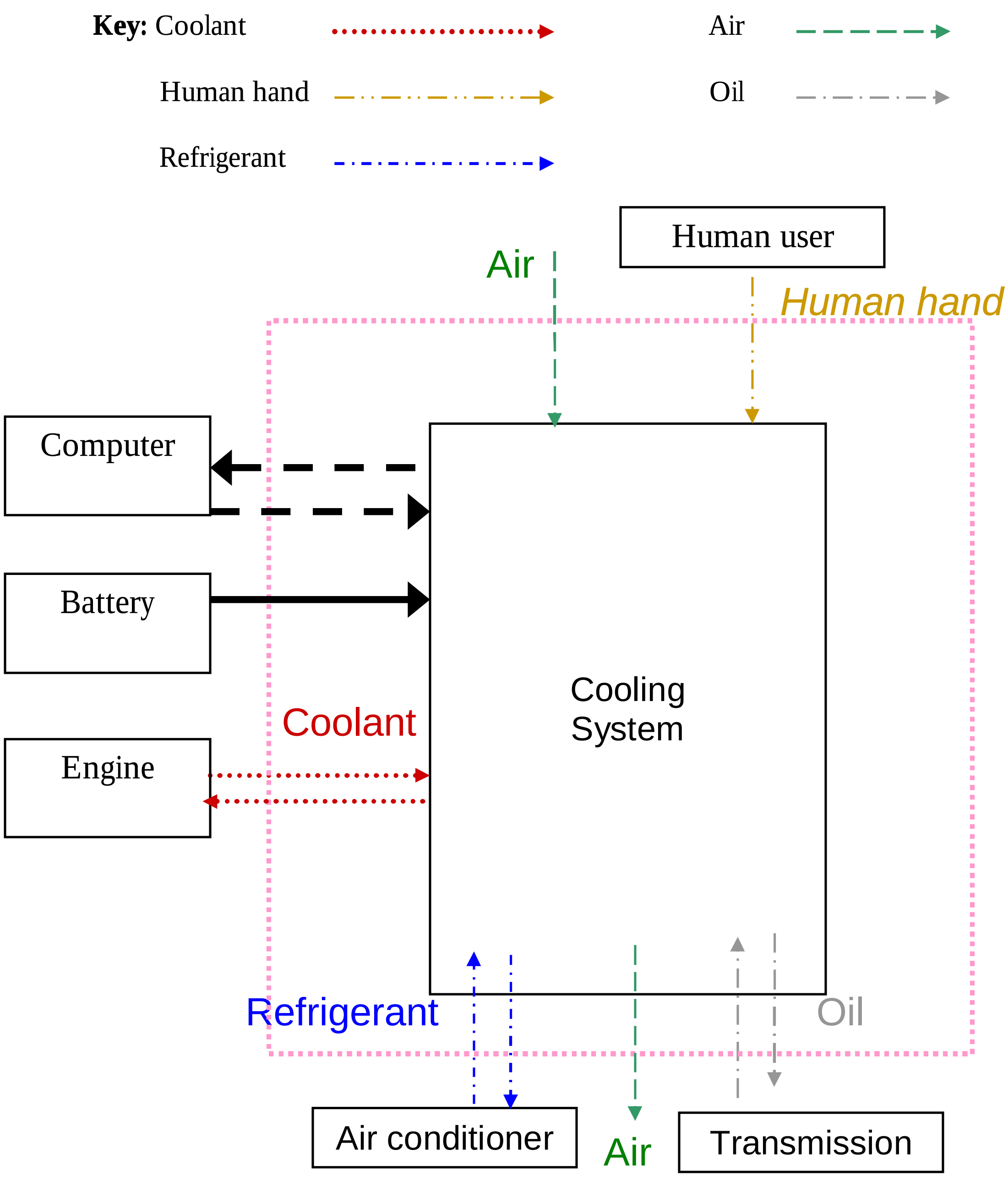


Figure 4.3 System Diagram at the System Level

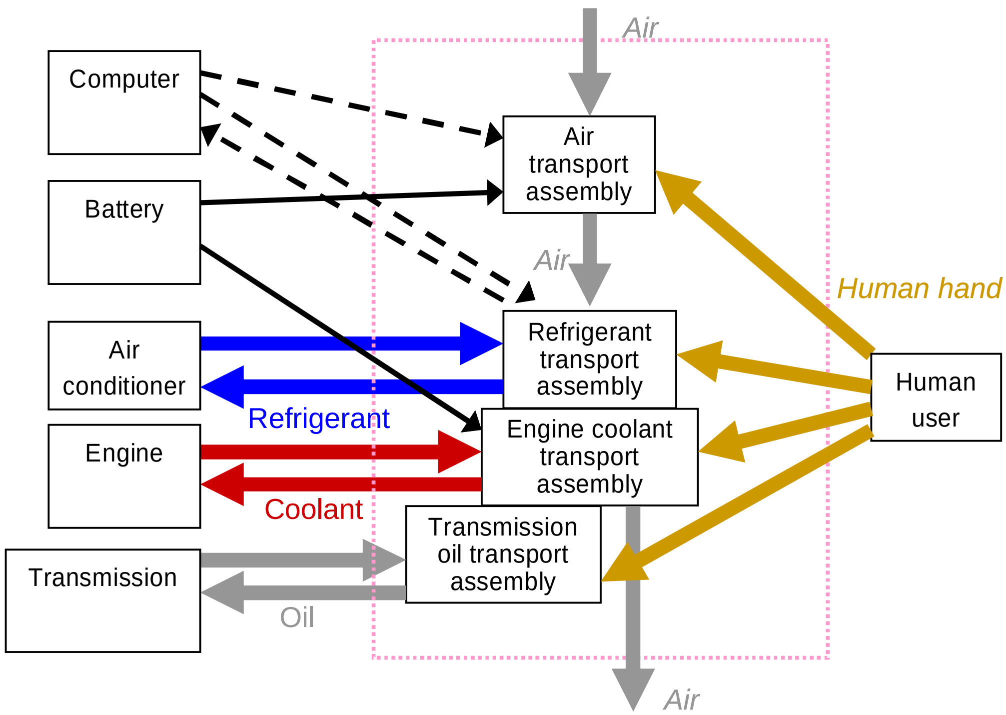


Figure 4.4 System Diagram at the Assembly Level

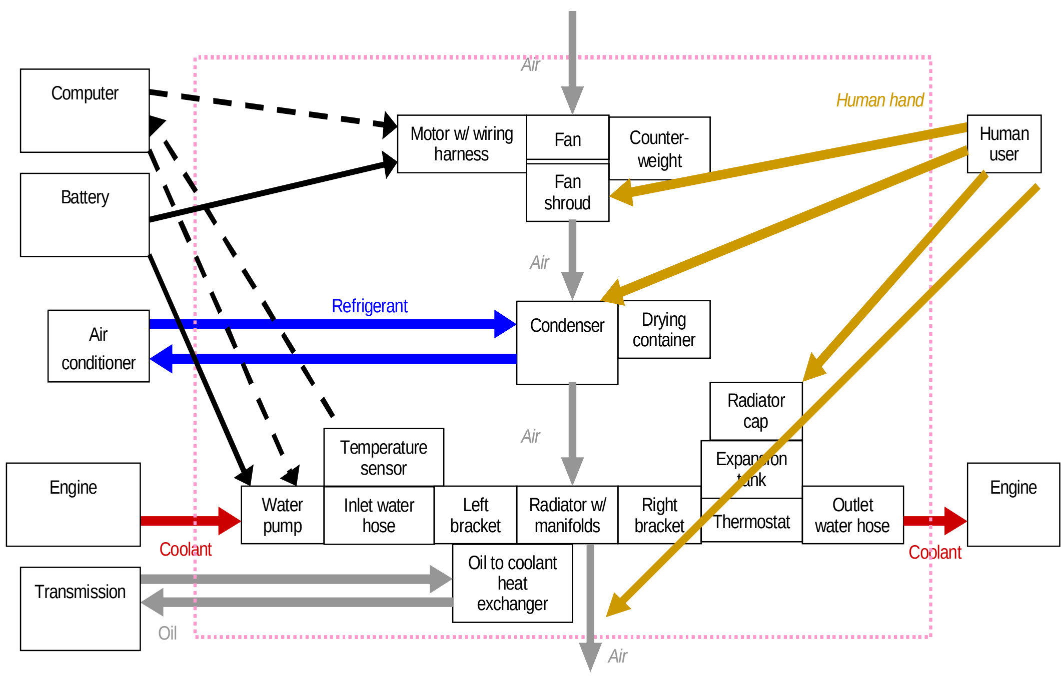


Figure 4.5 System Diagram at the Component Level

Assumptions related to the target system are then documented as listed as below:

1. The engine, transmission, cabin air conditioning system, cabin heating system, and electronic control unit are outside of the system boundary.

   Source: BMW vehicle technology representative

2. The vehicle has an automatic transmission, allowing the liquid-liquid heat exchanger to be considered inside the system boundary.

   Source: BMW vehicle technology representative

3. Only components that have major functions are included within the system boundaries. In addition, the small brackets, pipes, hoses, seals, gaskets, nuts, bolts, clamps and other small parts are included with the major functional components to which they are attached thereby simplifying the model from approximately 80 components to approximately 20.

   Source: Per team discussion

4. All system level functional requirements are tested.

   Source: Per team discussion

4.2.1.2 Phase 1

The requirements of the target system at the system, assembly and component levels are identified from the *lastenheft* provided by the BMW vehicle technology representative are categorized as functional and non-functional based on the guidance provided in section 3.3.2, step 2.

Table 4.1 Categorizing Requirements as Functional and Non-Functional

Requirements	Functional/Non-functional
Maintain engine temperature within operating range	Functional
Maintain transmission temperature within operating range	Functional

Table 4.1 Categorizing Requirements as Functional and Non-Functional (Continued)

Requirements	Functional / Non-functional
Maintain cabin temperature within comfort range	Functional
Pass wading depth test without failure	Functional
Pass acceleration test without failure	Functional
Pass vibration test without failure	Functional
Pass corrosion test without failure	Functional
Not fail under excess pressure	Functional
Not leak fluids into the environment	Functional
Prevent injuring the user	Functional
Be secured to the vehicle frame	Functional
Minimum clearance to engine mounted components in X-direction should be 30 mm	Non-Functional
Minimum clearance to engine mounted components in Y-direction should be 30 mm	Non-Functional
Minimum clearance to engine mounted components in Z-direction should be 20 mm	Non-Functional
Quick fit connectors for all hoses	Non-Functional
Mix-up proof hose connections	Non-Functional
Assembly vertically from underneath should be with a minimum clearance 12mm	Non-Functional
Vacuum assisted filling process for engine coolant would be 18mbara for 25seconds duration	Non-Functional
Ambient temperatures outside the vehicle should be -40°C to +120°C	Non-Functional
Coolant temperatures must be -40°C to +140°C	Non-Functional
Pressures should be 18mbarA to 3.5barA	Non-Functional
Should use common parts internally and externally for reduced development costs tooling investment	Non-Functional
Must be of Uniform periphery	Non-Functional
Should use closed air ducting for cooling system	Non-Functional
Must have mounting brackets for module to include thermostat unit	Non-Functional
Total frontal area of mesh ca. 26dm2 (580mm x 449mm)	Non-Functional
Mesh depth max. 30mm	Non-Functional

Table 4.1 Categorizing Requirements as Functional and Non-Functional (Continued)

Requirements	Functional/Non-functional
Optional low temperature radiator for automatic transmission ca. $4.7dm^2$	Non-Functional
Leak rate 150 l/min at 300mm	Non-Functional
In- and outlet should be with a nominal width (NW) 32mm	Non-Functional
Bleeding outlet (integrated in inlet connector) should be NW 12mm	Non-Functional
Overflow outlet should be NW 12mm	Non-Functional

Next, the functions for the system, assembly and component levels of the target system are identified from the requirements list, based on the definition of function given in the glossaries. Typically, a functional requirement becomes a function. Listing the functions at the system, assembly and the component level forms the function hierarchy. The entities in the hierarchy are differentiated using the numbering scheme as shown in the function list below.

Table 4.2 Function List

Function List
1.1 maintain engine temperature within operating range
1.1.1 transport air across the engine coolant transport assembly
1.1.1.1 Turn the fan when activated by the computer
1.1.2 transport coolant from the engine
1.1.2.1 Allow engine coolant to pass through if above a certain temperature
1.1.2.2 Not allow engine coolant to pass through if below a certain temperature
1.1.2.3 Send a signal to the computer indicating the engine coolant temperature
1.1.2.4 Pump engine coolant through the engine coolant transport assembly
1.1.3 allow heat to escape from coolant to the air
1.1.3.1 Store heat absorbed from the engine
1.1.4 transport coolant back to the engine 1.1.4.1 store excess engine coolant
1.1.4.2 Pump engine coolant through the engine coolant transport assembly

Table 4.2 Function List (Continued)

Function List
1.1.5 allow engine coolant to be added
1.1.6 allow engine coolant to be drained
1.2 maintain transmission temperature within operating range
1.2.1 transport oil from the transmission
1.2.2 allow heat to transfer to/from the engine coolant
1.2.2.1 Store heat absorbed from the transmission
1.2.3 transport oil back to the transmission
1.3 maintain cabin temperature within comfort range
1.3.1 transport air across the refrigerant transport assembly
1.3.1.1 Turn the fan when activated by the computer
1.3.2 allow heat to escape from refrigerant to the air
1.3.2.1 Store water trapped in the refrigerant transport assembly
1.3.2.2 Store heat absorbed from the cabin
2.1 pass wading depth test without failure
2.2 pass acceleration test without failure
2.3 pass vibration test without failure
2.3.1 balance the fan to prevent vibrations
2.4 pass corrosion test without failure
2.5 not fail under excess pressure
2.5.1 pass burst pressure test without failure
2.5.2 pass pressure swell test without failure
3.1 not leak fluids into the environment
4.1 prevent cutting the user
4.2 prevent burning the user
5.1 be secured to the vehicle frame

To populate the matrix, the requirements from the requirements list are entered in the row headings of the requirements to functions matrix in the Excel template. The functional requirements are listed first, followed by the non-functional ones. Functions are listed in a hierarchical order in the column headings. After the requirements and functions are entered, the matrix is populated. If there is a correlation between a requirement and a function, a 1 is entered in the matrix at the corresponding cell. If there is no correlation, a 0 is entered. These relationships are verified to eliminate inconsistencies. The Excel sheet color codes a cell with correlation in green and a cell without a correlation in yellow and then automatically calculates the row sums and column sums. A sample of the populated requirements to functions matrix is shown in Figure 4.6.

	A	B	C	D	E	F	G	H	I
1	**Requirements x Functions**	1.1.1 transport air across the engine coolant transport assembly	1.1.1.1 Turn the fan when activated by the computer	1.1.2 transport coolant from the engine	1.1.2.1 Allow engine coolant to pass through if above a certain temperature	1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	1.1.2.4 Pump engine coolant through the engine coolant transport assembly	1.1.3 allow heat to escape from coolant to the air
2	1.1 maintain engine temperature within operating	1	1	1	1	1	1	1	1
3	1.2 maintain transmission temperature within	0	0	0	0	0	0	0	0
4	1.3 maintain cabin temperature within comfort	0	0	0	0	0	0	0	0
5	2.1 pass wading depth test without failure	0	0	0	0	0	0	0	0
6	2.2 pass acceleration test without failure	0	0	0	0	0	0	0	0
7	2.3 pass vibration test without failure	0	0	0	0	0	0	0	0

Figure 4.6 A Sample of Populated Requirements to Function Matrix

4.2.1.3 Phase 2

A working principle is defined as a means by which a function is accomplished. For example, the function dissipate heat can be accomplished by either forced or natural convection. The working principles for each function in the function list are shown in Table 4.3.

Table 4.3 Working Principles List

Function list	Working Principles
1.1.1 transport air across the engine coolant transport assembly	take advantage of speed of the outside air relative to vehicle speed, force air
1.1.1.1 Turn the fan when activated by the computer	force air
1.1.2 transport coolant from the engine	forced transport
1.1.2.1 Allow engine coolant to pass through if above a certain temperature	mechanical orifice
1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	mechanical orifice
1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	electrical signal
1.1.2.4 Pump engine coolant through the engine coolant transport assembly	forced transport
1.1.3 allow heat to escape from coolant to the air	forced convection
1.1.3.1 Store heat absorbed from the engine	thermal capacitance
1.1.4 transport coolant back to the engine	forced transport
1.1.4.1 store excess engine coolant	closed container
1.1.4.2 Pump engine coolant through the engine coolant transport assembly	forced transport
1.2.1 transport oil from the transmission	forced transport
1.2.2 allow heat to transfer to/from the engine coolant	forced convection
1.2.2.1 Store heat absorbed from the transmission	thermal capacitance
1.2.3 transport oil back to the transmission	forced transport
1.3.1 transport air across the refrigerant transport assembly	take advantage of speed of outside air relative to vehicle speed, force air
1.3.1.1 Turn the fan when activated by the computer	force air
1.3.2 allow heat to escape from refrigerant to the air	forced convection
1.3.2.1 Store water trapped in the refrigerant transport assembly	closed container
1.3.2.2 Store heat absorbed from the cabin	thermal capacitance
2.1.1 Carry ### forces exerted by water	rigid connection
2.1.2 Not short electronics from water	electrical insulation
2.2.1 Carry ### forces from x direction acceleration	rigid connection
2.2.2 Carry ### forces from y direction acceleration	rigid connection

Table 4.3 Working Principles List (Continued)

Function list	Working Principles
2.2.3 Carry ### forces from z direction acceleration	rigid connection
2.3.1 Carry ### forces from other vibrating components	rigid connection
2.3.2 Balance the fan to prevent vibrations	counterbalance
2.4.1 Do not corrode in the presence of water, salt, etc.	non-corroding materials, shield corroding materials
2.5.1 Carry ### forces from pressurizing system	rigid connection
3.1.1 Do not leak fluids into the environment	tight connections, impervious to punctures
4.1.1 Prevent cutting the user	round edges, shield sharp edges
4.1.2 Prevent burning the user	keep surfaces cool, shield hot surfaces
5.1.1 Transmit forces to the vehicle frame	rigid connection

To populate the matrix, the functions from the requirements to functions matrix are automatically entered in the row headings of the functions to working principles matrix in the Excel template. Working principles are listed in the column headings. After the functions and working principles are entered into the requirements to functions matrix, it is populated. If there is a correlation between a function and a working principle, a 1 is entered in the matrix at the corresponding cell. If there is no correlation, a 0 is entered. These relationships are verified to eliminate inconsistencies. A sample of the populated functions to working principles matrix is shown in Figure 4.7.

	A	B	C	D	E	F	G	H	I
1	Functions x Working Principles	take advantage of speed of outside air relative to vehicle speed	force air	forced transport	mechanical orifice	electrical signal	forced convection	thermal capacitance	closed container
2	1.1.1 transport air across the engine coolant transport assembly	1	1	0	0	0	0	0	0
3	1.1.1.1 Turn the fan when activated by the computer	0	1	0	0	0	0	0	0
4	1.1.2 transport coolant from the engine	0	0	1	0	0	0	0	0
5	1.1.2.1 Allow engine coolant to pass through it above a certain temperature	0	0	0	1	0	0	0	0
6	1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	0	0	0	1	0	0	0	0
7	1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	0	0	0	0	1	0	0	0

Figure 4.7 A Sample of Functions to Working Principles Matrix

4.2.1.4 Phase 3

Each entity in the system boundary along with its corresponding mass is listed as seen in Table 4.4, which shows the system in bold and assemblies as italicized.

Table 4.4 Component Mass List

Assembly/Sub-assembly/Component list	Mass in grams
1. Cooling System	**27525**
1.1 Air transport assembly	*4701*
1.1.1 Motor subassembly	3500
1.1.2 Fan	700
1.1.3 Counterweight	1
1.1.4 Fan shroud	500
1.2 Engine transport assembly	*16726*
1.2.1 Thermostat	83
1.2.2 Expansion tank subassembly	884
1.2.3 Radiator cap	40
1.2.4 Radiator subassembly	5000
1.2.5 Left bracket	249
1.2.6 Right bracket	249
1.2.7 Inlet water hose	300
1.2.8 Outlet water hose	300
1.2.9 Temperature sensor	20
1.2.10 Water pump subassembly	4680

Table 4.4 Component Mass List (Continued)

Assembly/Sub-assembly/Component list	Mass in grams
1.2.11 Engine coolant	4921
1.3 Transmission oil assembly	*1598*
1.3.1 Liquid-liquid heat exchanger subassembly	598
1.3.2 Transmission oil	1000
1.4 Refrigerant transport assembly	*4500*
1.4.1 Drying container	300
1.4.2 Condenser subassembly	2200
1.4.3 Refrigerant	2000

Pictures of the components in the final list are grouped into their corresponding assemblies and shown in figures 4.8 – 4.11.

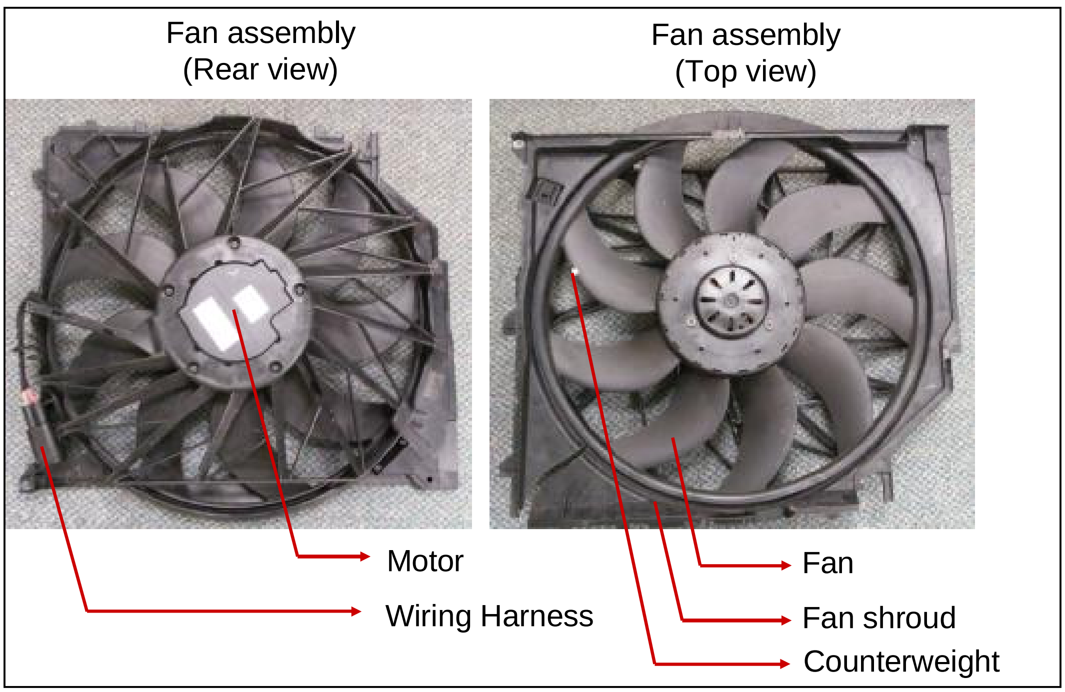


Figure 4.8 Components of the Air Transport Assembly

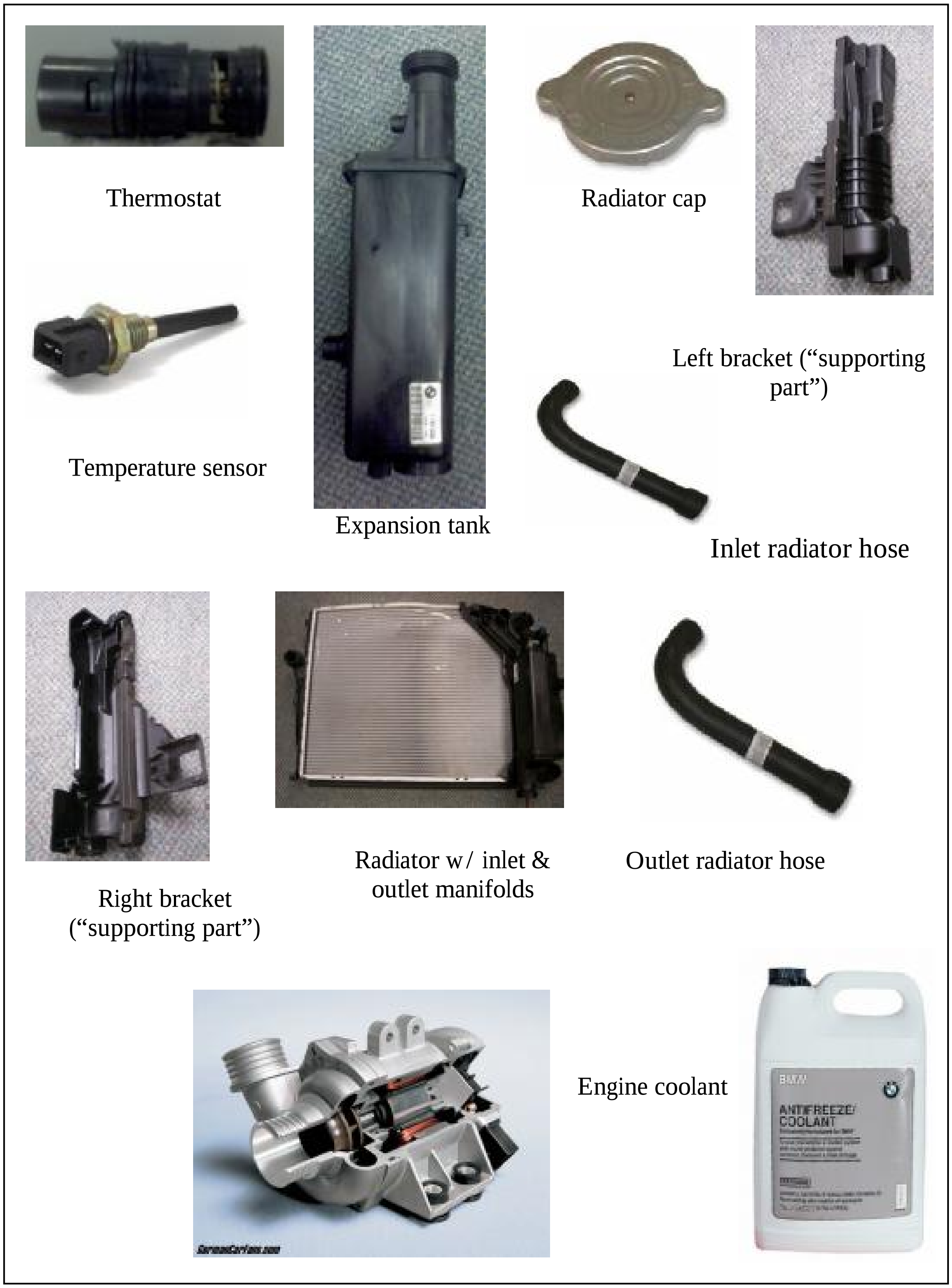


Figure 4.9 Components of the Engine Coolant Transport Assembly

Liquid – Liquid heat exchanger

Transmission oil

Figure 4.10 Components of the Transmission Oil Transport Assembly

Drying container

Condenser

Refrigerant

Figure 4.11 Components of the Refrigerant Transport Assembly

To populate the matrix, the working principles from the functions to working principles matrix are automatically entered in the row headings of the working principles to components matrix in the Excel template. Components are listed in the column headings After the components and working principles are entered into the working principles to components matrix, it is populated. If there is a correlation between a working principle and a component, a 1 is entered in the matrix at the corresponding cell. If there is no correlation, a 0 is entered. These relationships are verified to eliminate inconsistencies. A sample of the populated working principles to components matrix is shown in Figure 4.12.

	A	B	C	D	E	F	G	H	I	J	K	L
1	**Working Principles x Components**	**1. Cooling system**	**1.1 Air transport assembly**	**1.1.1 Motor subassembly**	**1.1.2 Fan**	**1.1.3 Counterweight**	**1.1.4 Fan shroud**	**1.2 Engine coolant transport assembly**	**1.2.1 Thermostat**	**1.2.2 Expansion tank subassembly**	**1.2.3 Radiator cap**	**1.2.4 Radiator subassembly**
2	**take advantage of speed of outside air relative to vehicle speed**	1	1	0	0	0	1	0	0	0	0	0
3	**force air**	1	1	1	1	0	1	0	0	0	0	0
4	**forced transport**	1	0	0	0	0	0	1	0	0	0	0
5	**mechanical orifice**	1	0	0	0	0	0	1	1	0	0	0

Figure 4.12 A Sample of Populated Working Principles to Components Matrix

4.2.1.5 Phase 4

The controllable parameters for the assembly, sub-assembly and components of the cooling system are determined. These parameters include the geometry, material and performance parameters. For example, the controllable parameters of the cooling system are maximum thermal dissipation, maximum electrical power draw, total solid and liquid volume and average density. Likewise, controllable parameters for all the items (assembly, sub-assembly and components) in the system boundary are determined. After the mutual consent of the team, the list is finalized as seen in Table 4.5, which shows the system and its parameters in bold and the assemblies and its parameters as italicized.

Table 4.5 Controllable Parameters List

Assembly, sub-assembly and components	Controllable parameters
1. Cooling System	**Maximum thermal dissipation, maximum electrical power draw, total solid & liquid volume, average density (4)**
1.1 Air transport assembly	*Max air flow produced, max electrical draw, total volume, average density (4)*
1.1.1 Motor subassembly	Max electrical power draw, max torque delivered, average density, depth, diameter (5)
1.1.2 Fan	Number of blades, depth, diameter, blade thickness, average density (5)
1.1.3 Counterweight	Solid volume, density (2)
1.1.4 Fan shroud	Depth, diameter, density (2)
1.2 Engine transport assembly	*Max thermal power dissipation, max electrical power draw, total solid and liquid volume, average density (4)*
1.2.1 Thermostat	Solid volume, average density, open temperature (3)
1.2.2 Expansion tank subassembly	Solid volume, liquid volume, thickness, density (4)
1.2.3 Radiator cap	Solid volume, average density (2)
1.2.4 Radiator subassembly	Solid volume, average density, liquid volume, depth front area, cooling fin area (6)
1.2.5 Left bracket	Solid volume, average density (2)
1.2.6 Right bracket	Solid volume, average density (2)
1.2.7 Inlet water hose	Thickness, average density, interior diameter, length (4)
1.2.8 Outlet water hose	Thickness, average density, interior diameter, length (4)
1.2.9 Temperature sensor	Solid volume, average density (2)
1.2.10 Water pump subassembly	Max electrical power draw, max flow rate delivered, average density, depth, diameter (5)
1.2.11 Engine coolant	Thermal capacitance, density (2)
1.3 Transmission oil assembly	*Maximum thermal power dissipation, max electrical power draw, total solid & liquid volume, average density (4)*

Table 4.5 Controllable Parameters List (Continued)

Assembly, sub-assembly and components	Controllable parameters
1.3.1 Liquid-liquid heat exchanger subassembly	Solid volume, average density, liquid volume (3)
1.3.2 Transmission oil	Thermal capacitance, density (2)
1.4 Refrigerant transport assembly	*Max thermal power dissipation, total solid and liquid volume, average density (3)*
1.4.1 Drying container	Solid volume, average density, liquid volume (3)
1.4.2 Condenser subassembly	Solid volume, average density, liquid volume, front area, cooling fin area (6)
1.4.3 Refrigerant	Thermal capacitance as liquid, density as liquid, thermal capacitance as vapor, density as vapor (4)

To populate the matrix, components from the working principles to components matrix are automatically entered in the row headings of the components to controllable parameters matrix in the Excel template, while the controllable parameters form the column headings. Once this process is completed, the matrix is populated. If there is a correlation between a component and a controllable parameter, a 1 is entered in the matrix in the corresponding cell. If there is no correlation, a 0 is entered. These relationships are then verified to eliminate inconsistencies. A sample of the populated components to controllable parameter matrix is shown in Figure 4.13.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Components x Component Parameters	Max thermal power dissipation	Max electrical power draw	Solid volume	Liquid volume	Average density	Max air flow produced	Max torque delivered	Depth	Diameter	Number of blades	Blade thickness
2	1. Cooling system	1	1	1	1	1	0	0	0	0	0	0
3	1.1 Air transport assembly	0	1	1	0	1	1	0	0	0	0	0
4	1.1.1 Motor subassembly	0	1	0	0	1	0	1	1	1	0	0
5	1.1.2 Fan	0	0	0	0	1	0	0	1	1	1	1
6	1.1.3 Counterweight	0	0	1	0	1	0	0	0	0	0	0
7	1.1.4 Fan shroud	0	0	0	0	1	0	0	1	1	0	0
8	1.2 Engine coolant transport assembly	1	1	1	1	1	0	0	0	0	0	0

Figure 4.13 A Sample of Populated Components to Controllable Parameters Matrix

4.2.1.6 Phase 5

Based on the specification in the *lastenheft*, tests for the functional requirements are listed. Tests like heat transfer test and user safety tests not specified in the *lastenheft* are manually generated. In addition, parameters measured by each test are listed thereby forming the test measures list. By mutual consent of the team, the tests and test measures list are finalized. The finalized list is shown in Table 4.6.

Table 4.6 Test Measures List

Tests	Test Measures
1. Wading depth test	Electrical damage, physical damage (2)
2. Acceleration test	Physical damage (1)
3. Vibration test	Excessive amplitudes, frequencies near natural frequencies (2)
4. Pressure swell test for ATF	Failure of any component in the transmission oil transport assembly (1)
5. Pressure swell test for coolant	Failure of any component in the engine coolant transport assembly (1)
6. Burst pressure test for ATF	Bursting of any component in the transmission oil transport assembly (1)
7. Burst pressure test for coolant	Bursting of any component in the engine coolant transport assembly (1)

Table 4.6 Test Measures List (Continued)

Tests	Test Measures
8. Corrosion test	Presence of corrosion in any component (1)
9. Leak test	Presence of leaks from any component (1)
10. Heat transfer from engine test	Heat transferred from engine (1)
11. Heat transfer from transmission test	Heat transferred to/from transmission (1)
12. Heat transfer from cabin test	Heat transferred from cabin (1)
13. User safety test	Presence of sharp edges, presence of hot surfaces (2)

These tests are listed in the column headings of the test measure to test matrix, while the test measures are entered in the row headings. If there is a correlation between a test and a test measure, a 1 is entered in the matrix at the corresponding cell. If there is no correlation, a 0 is entered. The correlations are then verified to eliminate inconsistencies. Both row and column sums are calculated automatically using the Excel sheet. A sample of the populated test to test measures matrix is shown in Figure 4.14.

	A	B	C	D	E	F	G
1	Test Measures x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF
2	Electrical damage	1	0	0	0	0	0
3	Physical damage	1	1	0	0	0	0
4	Vibration amplitude	0	0	1	0	0	0
5	Vibration frequency	0	0	1	0	0	0
6	Failure of component in oil transport assembly	0	0	0	1	0	0
7	Failure of component in engine coolant transport assembly	0	0	0	0	1	0
8	Bursting of component in oil transport assembly	0	0	0	0	0	1
9	Bursting of component in engine coolant transport assembly	0	0	0	0	0	0

Figure 4.14 A Sample of Test Measures to Tests Matrix

4.2.1.7 Phase 6

The controllable parameters from the component to controllable parameters matrix are entered automatically into the row headings of the controllable parameters to test measures matrix, while the test measures are entered automatically into the column headings. The column beside each component parameter is populated by entering a {-1, 0, 1} indicating whether decreasing -1 or increasing +1 the component parameter is likely to reduce the mass of the associated component or if there is no clear relationship 0. For example, -1 is entered for the controllable parameter maximum electrical power draw because a change in this parameter will have a negative effect on the test measure. Next, the row below the test measure is populated by asking “if each component parameter is changed in the direction indicated (in the first column) to reduce mass, what will be its effect on each test measure?” For example, -1 is placed next to the test measure “electrical damage” because decreasing the electrical damage is likely to reduce the mass of the associated component i.e., motor. The remaining sections of the controllable parameters to test measures matrix is populated by examining the correlation between each component parameter and test measures. For example, a decrease in the controllable parameter “max electrical power draw” as indicated by the -1 in the column, decreases the effect on the test measure electrical damage. Therefore, a -1 is entered at the corresponding cell in the matrix. Similarly, the rest of the controllable parameters to test measures matrix is populated. A sample of the controllable parameters to test measures matrix is shown in Figure 4.15.

	A	B	C	D	E	F	G	H	I	J
1	Component Parameters x Test Measures		Electrical damage	Physical damage	Vibration amplitude	Vibration frequency	Failure of component in oil transport assembly	engine coolant transport assembly	Bursting of component in oil transport assembly	engine coolant transport assembly
2	Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) ⇒	Direction to change Cpt. Param. to decrease mass (+1 = up, -1 = down, 0 = unclear) ⇩	-1	-1	-1	1	-1	-1	-1	-1
3	Max thermal power dissipation	0	0	0	0	0	0	0	0	0
4	Max electrical power draw	-1	-1	0	0	0	0	0	0	0
5	Solid volume	-1	0	1	1	1	0	0	0	0
6	Liquid volume	-1	0	0	1	1	0	0	-1	-1
7	Average density	-1	0	0	1	1	0	0	0	0
8	Max air flow produced	1	0	0	0	0	0	0	0	0
9	Max torque delivered	1	0	0	0	0	0	0	0	0
10	Depth	-1	0	0	1	1	0	0	0	0
11	Diameter	-1	0	0	1	1	0	0	0	0
12	Number of blades	-1	0	0	1	1	0	0	0	0

Figure 4.15 A Sample of Controllable Parameters to Test Measures Matrix

Executing these seven phases completes the populating of the primary level matrices in the model.

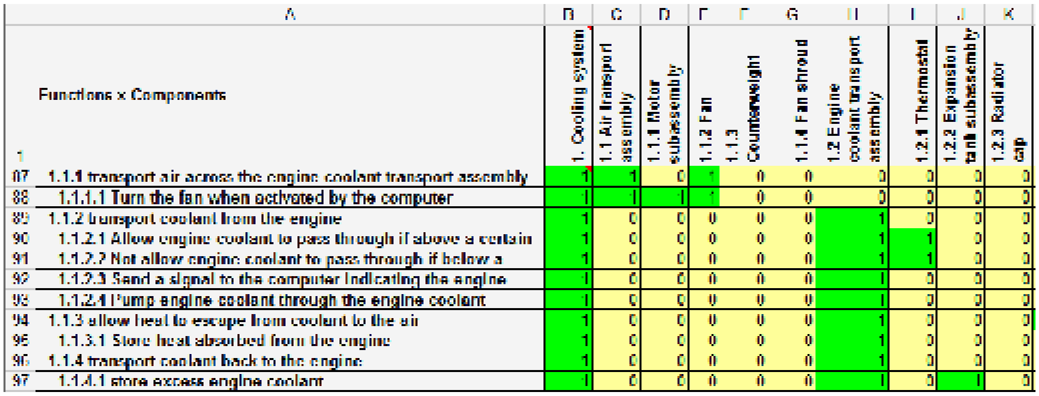
4.2.2 Consistency Check on the Matrices

Once the primary level matrices are populated, the matrices in the secondary to the sixth level are automatically generated in the Excel sheet through matrix multiplication and using the information entered in the primary level matrices. In order to conduct a consistency check for those matrices, 15 matrices in the secondary to sixth levels are manually populated and compared with their respective automatically generated ones. False positives and false negatives are examined to see if relationships are missed in these higher level matrices. Manually populated matrices are subsequently revised as appropriate. True positives and true negatives are also analyzed to ensure the consistency of each multiplied matrix. As it would be redundant and time-consuming to explain the procedure followed to perform the consistency check for all the 15 matrices in the secondary to sixth level, this process is explained only for the functions to components matrix at the second level.

Samples of both automatically generated and manually populated function to component matrix are shown in Figures 4.16 and 4.17 respectively.

	A	B	C	D	E	F	G	H	I	J	K
1	Functions x Components	1. Cooling system	1.1 Air transport assembly	1.1.1 Motor sub assembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap
2	1.1.1 transport air across the engine coolant transport assembly	2	2	1	1	0	2	0	0	0	0
3	1.1.1.1 Turn the fan when activated by the computer	1	1	1	1	0	1	0	0	0	0
4	1.1.2 transport coolant from the engine	1	0	0	0	0	0	1	0	0	0
5	1.1.2.1 Allow engine coolant to pass through if above a certain	1	0	0	0	0	0	1	1	0	0
6	1.1.2.2 Not allow engine coolant to pass through it below a	1	0	0	0	0	0	1	1	0	0
7	1.1.2.3 Send a signal to the computer indicating the engine	1	0	0	0	0	0	1	0	0	0
8	1.1.2.4 Pump engine coolant through the engine coolant	1	0	0	0	0	0	1	0	0	0
9	1.1.3 allow heat to escape from coolant to the air	1	0	0	0	0	0	1	0	0	0
10	1.1.3.1 Store heat absorbed from the engine	1	0	0	0	0	0	1	0	0	0
11	1.1.4 transport coolant back to the engine	1	0	0	0	0	0	1	0	0	0
12	1.1.4.1 store excess engine coolant	1	0	0	0	0	0	1	0	1	1

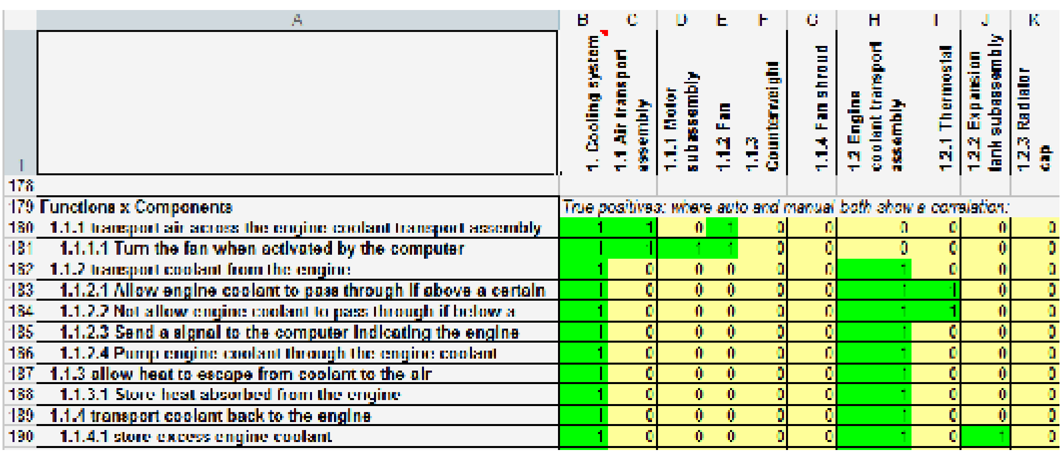
Figure 4.16 A Sample of Automatically Generated Function to Component Matrix



	A	B	C	D	E	F	G	H	I	J	K
1	Functions x Components	1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap
87	1.1.1 transport air across the engine coolant transport assembly	1	1	0	1	0	0	0	0	0	0
88	1.1.1.1 Turn the fan when activated by the computer	1	1	1	1	0	0	0	0	0	0
89	1.1.2 transport coolant from the engine	1	0	0	0	0	0	1	0	0	0
90	1.1.2.1 Allow engine coolant to pass through if above a certain	1	0	0	0	0	0	1	1	0	0
91	1.1.2.2 Not allow engine coolant to pass through if below a	1	0	0	0	0	0	1	1	0	0
92	1.1.2.3 Send a signal to the computer indicating the engine	1	0	0	0	0	0	1	0	0	0
93	1.1.2.4 Pump engine coolant through the engine coolant	1	0	0	0	0	0	1	0	0	0
94	1.1.3 allow heat to escape from coolant to the air	1	0	0	0	0	0	1	0	0	0
95	1.1.3.1 Store heat absorbed from the engine	1	0	0	0	0	0	1	0	0	0
96	1.1.4 transport coolant back to the engine	1	0	0	0	0	0	1	0	0	0
97	1.1.4.1 store excess engine coolant	1	0	0	0	0	0	1	0	1	0

Figure 4.17 A Sample of Manually Populated Function to Component Matrix

Once a matrix is manually populated, true positives, true negatives, false positives and false negatives are automatically generated in the Excel template. True positives, which refer to the cells that show a correlation in both automatically generated matrix and manually populated matrix, are shaded in the matrix as shown in Figure 4.18.



	A	B	C	D	E	F	G	H	I	J	K
1		1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap
178											
179	Functions x Components	True positives: where auto and manual both show a correlation:									
180	1.1.1 transport air across the engine coolant transport assembly	1	1	0	1	0	0	0	0	0	0
181	1.1.1.1 Turn the fan when activated by the computer	1	1	1	1	0	0	0	0	0	0
182	1.1.2 transport coolant from the engine	1	0	0	0	0	0	1	0	0	0
183	1.1.2.1 Allow engine coolant to pass through if above a certain	1	0	0	0	0	0	1	1	0	0
184	1.1.2.2 Not allow engine coolant to pass through if below a	1	0	0	0	0	0	1	1	0	0
185	1.1.2.3 Send a signal to the computer indicating the engine	1	0	0	0	0	0	1	0	0	0
186	1.1.2.4 Pump engine coolant through the engine coolant	1	0	0	0	0	0	1	0	0	0
187	1.1.3 allow heat to escape from coolant to the air	1	0	0	0	0	0	1	0	0	0
188	1.1.3.1 Store heat absorbed from the engine	1	0	0	0	0	0	1	0	0	0
189	1.1.4 transport coolant back to the engine	1	0	0	0	0	0	1	0	0	0
190	1.1.4.1 store excess engine coolant	1	0	0	0	0	0	1	0	1	0

Figure 4.18 A Sample of Manually Populated Function to Component Matrix Showing True Positives

True negatives, which refer to the cells that do not show a correlation in both automatically generated matrix and manually populated matrix, represented by the cells that are not shaded in the matrix as shown in Figure 4.19.

	A	B	C	D	E	F	G	H	I	J	K
1		1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap
406		True negatives: auto and manual both do not show a correlation:									
407	Functions x Components	(yellow cells indicate true negatives)									
408	1.1.1 transport air across the engine coolant transport assembly	1	1	1	1	0	1	0	0	0	0
409	1.1.1.1 Turn the fan when activated by the computer	1	1	1	1	0	1	0	0	0	0
410	1.1.2 transport coolant from the engine	1	0	0	0	0	0	1	0	0	0
411	1.1.2.1 Allow engine coolant to pass through if above a certain	1	0	0	0	0	0	1	1	0	0
412	1.1.2.2 Not allow engine coolant to pass through if below a	1	0	0	0	0	0	1	1	0	0
413	1.1.2.3 Send a signal to the computer indicating the engine	1	0	0	0	0	0	1	0	0	0
414	1.1.2.4 Pump engine coolant through the engine coolant	1	0	0	0	0	0	1	0	0	0
415	1.1.3 allow heat to escape from coolant to the air	1	0	0	0	0	0	1	0	0	0
416	1.1.3.1 Store heat absorbed from the engine	1	0	0	0	0	0	1	0	0	0
417	1.1.4 transport coolant back to the engine	1	0	0	0	0	0	1	0	0	0
418	1.1.4.1 store excess engine coolant	1	0	0	0	0	0	1	0	1	1

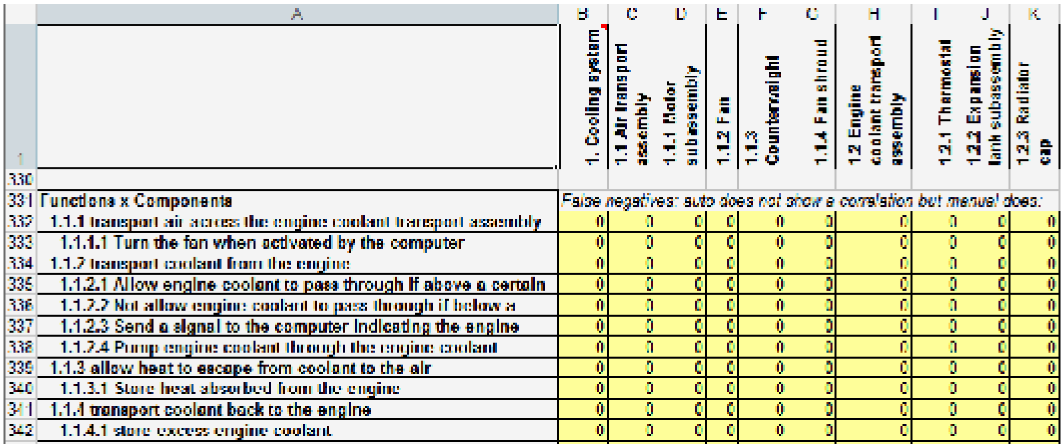
Figure 4.19 A Sample of Manually Populated Function to Component Matrix Showing True Negatives

False positives, which refer to the cells that show a correlation in the automatically generated matrix but do not show a correlation in the manually populated matrix, are shaded in the matrix as shown in Figure 4.20.

	A	B	C	D	E	F	G	H	I	J	K
1		1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap
254											
255	Functions x Components	False positives: auto shows a correlation that manual does not.									
256	1.1.1 transport air across the engine coolant transport assembly	0	0	1	0	0	1	0	0	0	0
257	1.1.1.1 Turn the fan when activated by the computer	0	0	0	0	0	1	0	0	0	0
258	1.1.2 transport coolant from the engine	0	0	0	0	0	0	0	0	0	0
259	1.1.2.1 Allow engine coolant to pass through if above a certain	0	0	0	0	0	0	0	0	0	0
260	1.1.2.2 Not allow engine coolant to pass through if below a	0	0	0	0	0	0	0	0	0	0
261	1.1.2.3 Send a signal to the computer indicating the engine	0	0	0	0	0	0	0	0	0	0
262	1.1.2.4 Pump engine coolant through the engine coolant	0	0	0	0	0	0	0	0	0	0
263	1.1.3 allow heat to escape from coolant to the air	0	0	0	0	0	0	0	0	0	0
264	1.1.3.1 Store heat absorbed from the engine	0	0	0	0	0	0	0	0	0	0
265	1.1.4 transport coolant back to the engine	0	0	0	0	0	0	0	0	0	0
266	1.1.4.1 store excess engine coolant	0	0	0	0	0	0	0	0	0	1

Figure 4.20 A Sample of Manually Populated Function to Component Matrix Showing False Positives

False negatives, which refer to the cells that do not show a correlation in the automatically generated matrix but show a correlation in the manually populated matrix, are shaded in the matrix as shown in Figure 4.21.



	A	B	C	D	E	F	G	H	I	J	K
1		1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap
330											
331	Functions x Components	False negatives: auto does not show a correlation but manual does:									
332	1.1.1 transport air across the engine coolant transport assembly	0	0	0	0	0	0	0	0	0	0
333	1.1.1.1 Turn the fan when activated by the computer	0	0	0	0	0	0	0	0	0	0
334	1.1.2 transport coolant from the engine	0	0	0	0	0	0	0	0	0	0
335	1.1.2.1 Allow engine coolant to pass through if above a certain	0	0	0	0	0	0	0	0	0	0
336	1.1.2.2 Not allow engine coolant to pass through if below a	0	0	0	0	0	0	0	0	0	0
337	1.1.2.3 Send a signal to the computer indicating the engine	0	0	0	0	0	0	0	0	0	0
338	1.1.2.4 Pump engine coolant through the engine coolant	0	0	0	0	0	0	0	0	0	0
339	1.1.3 allow heat to escape from coolant to the air	0	0	0	0	0	0	0	0	0	0
340	1.1.3.1 Store heat absorbed from the engine	0	0	0	0	0	0	0	0	0	0
341	1.1.4 transport coolant back to the engine	0	0	0	0	0	0	0	0	0	0
342	1.1.4.1 store excess engine coolant	0	0	0	0	0	0	0	0	0	0

Figure 4.21 A Sample of Manually Populated Function to Component Matrix Showing False Negatives

The percentage of true positives and true negatives represents the consistency of the automatically generated matrix, while the percentage of the false positives and false negatives represent the inconsistency. These percentages are automatically generated in a pie-chart as shown in Figure 4.22.

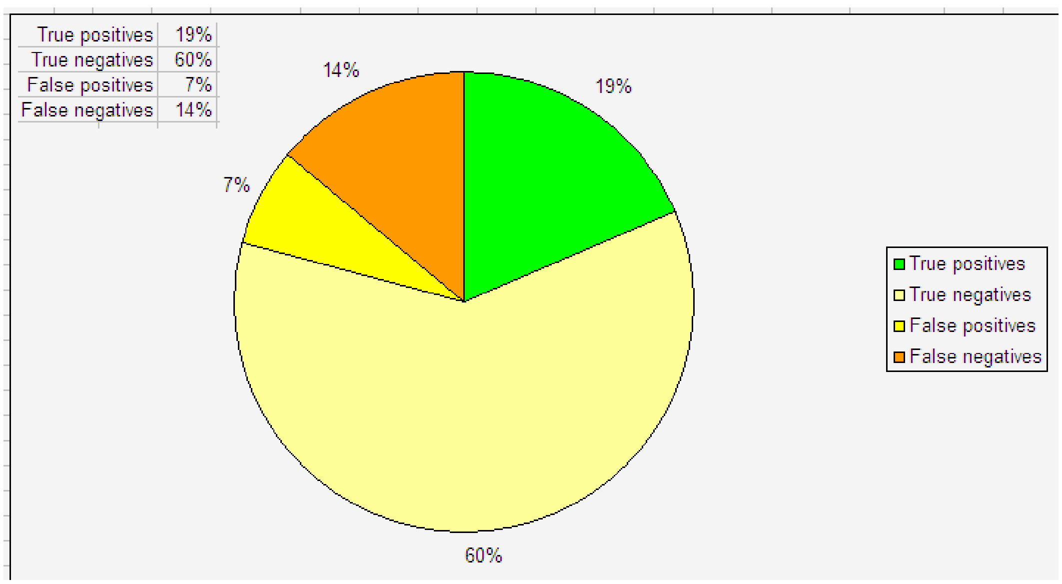


Figure 4.22 Pie Chart Showing the Distribution of Consistency Metrics

As it is advisable to have 100% consistency, the false positives and false negatives are examined to check if real relationships were missed in the higher level matrices. For example, the automatically generated matrix shows a correlation between the motor sub-assembly and the function 1.1.1 but the manually populated matrix does not. Since the motor sub-assembly is required to transport air across the engine coolant transport assembly, a 1 is entered in the manually populated matrix to correct this false negative. The same reasoning is applied to all false negatives and false positives to eliminate the inconsistencies and to improve the consistency metric. This procedure finally yielded a consistency metric of 94% and an inconsistency metric of 6%. As the inconsistency metric was very low, it was accepted by the mutual consent of the team. The distribution of the consistency metrics after consistency check is shown in Figure 4.23.

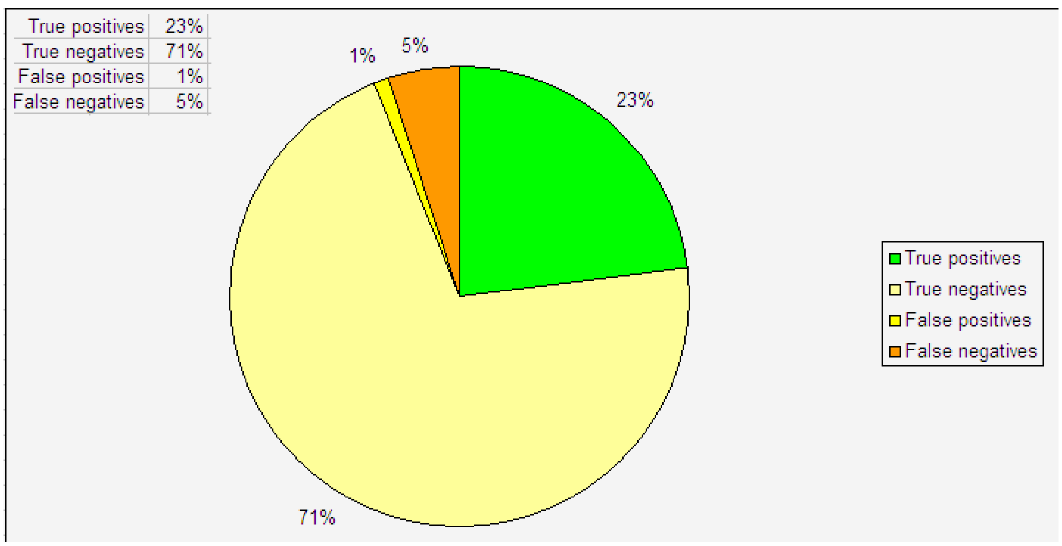


Figure 4.23 Pie Chart Showing the Distribution of Consistency Metrics After Consistency Check

Executing these steps, confirms the consistency of the matrices in the modeling scheme. Therefore, steps to find potential solutions to reduce mass can be executed. They are discussed in the next sub-section.

4.2.3 Generating Solutions to Reduce the System Mass

The seven solution strategies discussed in section 3.3.3, are applied to the cooling system to generate the following solutions and observations.

1. Identify solutions to reduce mass by removing non-functional requirements

Using the requirements to functions matrix, the impact of removing or modifying each non-functional requirement is examined. From the requirements to functions matrix, it is observed all the functional requirements map to functions. The non-functional requirements are captured in the matrix but they do not map to any requirements. Therefore, they do not multiply with any relationships in subsequent matrices. Hence, no solutions for the cooling system are found using this strategy.

2. Identify solutions to reduce mass by using alternate components embodying the existing working principles

Using the mass list, components with significant mass are identified as listed below.

System: Existing cooling system weighs ~27.5 kg.

Assembly: Mass distribution is approximately 60% for the engine coolant transport assembly, 17% for the air transport assembly, 16% for the refrigerant transport assembly and 6% for the transmission oil assembly.

Sub-assembly: The radiator is the heaviest subassembly, followed by the engine coolant, the water pump and the motor. As the number of components is reduced from 80 to ~20 based on the criticality of function, it is decided to consider all the components in the finalized list as components with significant mass. Using the working principles to components matrix, alternate components for those with significant mass that embody the existing working principles are identified and the following solutions are generated.

i. Replacing the electric motor and water pump with hydraulic motors

ii. Replacing the expansion tank and the drying container with fluid bladders.

These solutions strategies would save approximately 684 g, which is 2.3 % of the system mass, thereby yielding 2 solutions having the potential to save ~ 2.5% of the system mass.

3. Identify solutions to reduce mass by using alternate working principles

For the existing components, alternate working principles are identified. The solutions are identified by finding the appropriate components embodying the alternate working principle. The identified strategies included:

- Using the fluid carrying wheels as heat exchangers to convect heat to the air and conduct heat to the ground, thereby eliminating the radiator, condenser, and fan among others. Doing so would eliminate the radiator and condenser subassemblies, and the air transport assembly and potentially saving approximately 12 kg. Although the mass of the wheels and fluid couplings is difficult to estimate, an estimated 6 kg is added, yielding a net reduction in mass of 6 kg.
- Using a thermopile to convert heat into electricity to reduce alternator size and using thermoelectric cooling to reduce the front area or to eliminate radiator and/or condenser. Assuming that the additional mass of the thermopile would balance the reduction in the mass of the alternator, reducing the front area of radiator and condenser by 15% would save 1 kg.
- Replacing the drying container with a drip valve has the potential to save 150 g.

- Ducting more outside air across the radiator and condenser to reduce their front area. Doing so would result in the reduction of front area by approximately 15%, yielding a mass reduction of 1kg. Adding the mass of new ducts (~500 g), yields an overall mass reduction of ~500 g.
- Using rubber shock mounts to reduce the size of mounting brackets and fasteners. Doing so would result in approximately a 15% mass savings, yielding ~100 g.
- Radiating the heat to the surrounding environment
- Using heat pipes instead of forced convection
- Eliminating pump for forced convection and using natural convection
- Using water-tight enclosures for electrical components
- Replacing the glycol and refrigerant with environmentally safe chemicals
- Introducing the motor driven by heat directly
- Using a solenoid valve instead of a mechanical thermostat
- Using a steam turbine to recover waste heat
- Insulating the engine cylinders
- Introducing targeted cabin cooling

Overall, this solution strategy yielded 15 solutions resulting in a total reduction of 6 kg, approximately 20% of the cooling system mass.

4. Identify solutions to reduce mass by eliminating high mass, low function components

Components that exhibit low functionality are identified using the function to component matrix. Those that could be eliminated without having a negative impact on test measures are identified using the components to test measures matrix.

From the function to component matrix, it is observed that no components exhibit low functionality. Therefore, no solutions for the cooling system are found using this strategy.

5. Identify solutions to reduce mass by eliminating components that satisfy requirements that can be eliminated

Using the requirements to components matrix, requirements no longer needed are identified and listed as are the components that embody them. It is observed that no functional requirements can be eliminated. Removing non-functional requirements will have no effect on the model since they do not map through components to any other domain. Therefore, no solutions for the cooling system are found using this strategy.

6. Identify solutions to reduce mass by eliminating components that satisfy functions that can be eliminated

Using the functions to component matrix, functions no longer needed are identified and listed as are the components that embody them. It is observed that no functions can be removed. However, some lower level functions can be removed (or changed) by modifying the higher level working principles. Therefore, no solutions for the cooling system are found using this strategy.

7. Identify solutions to reduce mass by optimizing controllable parameters

Individual and group of components parameters (of components with significant mass) to change to reduce the mass, without negatively affecting the test measures are identified and listed using the controllable parameters to test measures matrix. This yielded the following solutions.

- Reducing the solid volume of all components using shape optimization, while satisfying loading and fatigue requirements
- Reducing liquid volume by making hoses shorter and smaller in diameter
- Reducing the mass of all components by using lower density materials of equal or better strength
- Increasing the cooling fin area on the radiator and the condenser to reduce their front areas
- Adding the cooling fin area to the fluid carrying components such as hoses and connections to reduce the front area of the radiator and condenser
- Using a smaller, higher efficiency motor and/or water pump that draws less electrical power
- Increasing the flow rate of all fluids by using faster motor and water pump in order to decrease the front area of the radiator and condenser and the fan size
- Adding a chemical to increase the thermal capacitance of the coolant and refrigerant to decrease the front area of the radiator and condenser and the fan size

This solution strategy yielded 8 solutions having the potential to save approximately 4 kg i.e., 15% of the cooling system mass.

These 7 solution strategies generated a total of 25 solutions.

4.2.4 Feasibility Study and Combination of Solutions

The feasibility of the solution is analyzed by conducting a basic analysis to predict if each solution would serve as a potential candidate for minimizing mass. Feasibility study is explained for a feasible solution and an infeasible solution.

Solution: Using a smaller, higher efficiency fan motor and/or water pump

This solution is obtained from the analysis of working principles to components matrix. A 600 watt brushless DC motor from the brand powerpack weighs ~2200 grams. It performs the intended functionality and results in an estimated mass savings of ~1300 grams. This solution is feasible because this motor can be easily replaced at a relatively low cost. In addition, the existing ECU can be used to control this new motor. However, the trade-off is that this replacement would require redesigning the fan and fan shroud to accommodate the different size motor.

Solution: Use rubber shock mounts to reduce the size of mounting brackets, bolts.

This solution is obtained from the analysis of functions to working principles matrix. Currently, the brackets and bolts attach the cooling system rigidly to the vehicle frame. Using the rubber shock mounts can eliminate fasteners but increases the cooling system mass by ~200g. Hence, this is an infeasible solution.

Performing similar studies for all 25 solutions resulted in 9 feasible and 16 infeasible solutions. The feasible solutions are listed below:

1. Using a smaller, higher efficiency motor and/or water pump that draws less electrical power
2. Reducing the solid volume of all components using shape optimization, while satisfying the loading and fatigue requirements
3. Reducing the mass of all components by using lower density materials of equal or better strength
4. Increasing the cooling fin area on the radiator and condenser to reduce their front area

5. Adding the cooling fin area to the fluid-carrying components such as hoses and connections to reduce the front area of the radiator and condenser.
6. Replacing the expansion tank and drying container with fluid bladders.
7. Targeting cabin cooling
8. Insulating engine cylinders
9. Replacing the radiator and condenser with closed-circuit vertical heat pipes.

The infeasible solutions are listed below:

1. Radiating the heat to the surrounding environment
2. Eliminating the pump and using natural convection
3. Using water-tight enclosures for the electrical components
4. Replacing glycol and refrigerant with environmentally safe chemicals
5. Using a motor directly driven by heat
6. Using a solenoid valve instead of the mechanical thermostat
7. Using a steam turbine to recover waste heat
8. Reducing the liquid volume by making hoses shorter and smaller in diameter
9. Increasing the flow rate of all fluids using faster motor and water pump to decrease the front area of the radiator and condenser and fan size
10. Adding a chemical to increase the thermal capacitance of the coolant and refrigerant in order to decrease front area of radiator and condenser and fan size
11. Replacing the electric motor and water pump with hydraulic motors and a hydraulic pump
12. Using rubber shock mounts to reduce the size of the mounting fasteners.

13. Using fluid-carrying wheels as heat exchangers to convect heat to the air and conduct heat to the ground, thereby eliminating the radiator, condenser, and fan among other components.
14. Using a thermopile to convert heat to electricity to reduce alternator size in conjunction with thermoelectric cooling to reduce the front area or possibly eliminate radiator and/or condenser
15. Replacing the drying container with a drip valve.
16. Ducting more outside air across the radiator and condenser to reduce their front area.

4.3 Fast Systematic Method

Since executing the comprehensive systematic method is time consuming, a compressed method is developed. Important steps from the comprehensive method (steps involving populating the matrices to feasibility study) that are required to generate solutions to reduce mass are selected after careful analysis and this resulted in a "fast" method. This method, proposed by the research associate involved in the BMW project, is called as the Multiple Matrix Method for Minimizing Mass (M^5 method). A case study to verify this method is conducted by the author. The case study involving the BMW Z4 cooling system is integrated with the steps in the method for the reader's convenience. Solution generating steps are bolded.

Requirements Analysis:

1. From the available documentation, the system requirements are identified and listed.

2. From the requirements list, the functional and non-functional requirements are distinguished and entered in the template.

3. The solutions are identified by **considering the impact of removing or modifying each non-functional requirement** and entered in the template as shown in Table 4.7.

Table 4.7 Requirements Analysis Template

Requirements	Functional?	Solution Ideas
1.1 maintain engine temperature within operating range	Functional	
1.2 maintain transmission temperature within operating range	Functional	
1.3 maintain cabin temperature within comfort range	Functional	
2.1 pass wading depth test without failure	Functional	
2.2 pass acceleration test without failure	Functional	
2.3 pass vibration test without failure	Functional	
2.4 pass corrosion test without failure	Functional	
2.5 not fail under excess pressure	Functional	
3.1 not leak fluids into the environment	Functional	
4.1 prevent injuring the user	Functional	
5.1 be secured to the vehicle frame	Functional	
Minimum clearance to engine mounted components in X-direction should be 30 mm	Non-Functional	
Minimum clearance to engine mounted components in Y-direction should be 30 mm	Non-Functional	
Minimum clearance to engine mounted components in Z-direction should be 20 mm	Non-Functional	
Quick fit connectors for all hoses	Non-Functional	Connectors could be sealed which might eliminate the quick fit mechanisms and components

Table 4.7 Requirements Analysis Template (Continued)

Requirements	Functional?	Solution Ideas
Mix-up proof hose connections	Non-Functional	
Assembly vertically from underneath should be with a minimum clearance 12mm	Non-Functional	
Vacuum assisted filling process for engine coolant would be 18mbara for 25seconds duration	Non-Functional	
Ambient temperatures outside the vehicle should be -40°C to +120°C	Non-Functional	
Coolant temperatures must be -40°C to +140°C	Non-Functional	
Pressures should be 18mbara to 3.5bara	Non-Functional	
Should use of common parts internally and externally for reduced development costs tooling investment	Non-Functional	
Must be of Uniform periphery	Non-Functional	
Should use closed air ducting for cooling system	Non-Functional	
Must have mounting brackets for module to include thermostat unit	Non-Functional	Thermostat can be mounted in the expansion tank. This might eliminate the mounting brackets
Total frontal area of mesh ca. 26dm2 (580mm x 449mm)	Non-Functional	
Mesh depth max. 30mm	Non-Functional	
Optional low temperature radiator for automatic transmission ca. 4.7dm2	Non-Functional	
Leak rate 150 l/min at 300mm	Non-Functional	
In- and outlet should be with a nominal width (NW) 32mm	Non-Functional	
Bleeding outlet (integrated in inlet connector) should be NW 12mm	Non-Functional	
Overflow outlet should be NW 12mm	Non-Functional	
Dimensions of oil cooler’s block size X=45mm; Y=165mm; Z=80mm	Non-Functional	

Table 4.7 Requirements Analysis Template (Continued)

Requirements	Functional?	Solution Ideas
Quick connectors for transmission fluid and engine coolant	Non-Functional	
Operating pressures transmission fluid should be in the range of 8bara at –40°C to +160°C	Non-Functional	
Pressures engine coolant should be in the range of 3bara at –40°C to +143°C	Non-Functional	
Leak proof tests for transmission fluid is minimum 20barg	Non-Functional	
Leak proof tests for engine coolant is minimum 2,5barg	Non-Functional	
Total frontal area of mesh of condenser should be 22.2dm^2	Non-Functional	Overall, the geometric specifications found in most of the non-fucntional requirements might have to be re-considered for any for a possibility of reducing the length/width/height. Lesser the geometry, lesser the mass.

3 solutions are generated using this step.

Component Analysis:

4. From the available documentation, the system, assemblies and sub-assemblies/components are identified along with their respective mass and listed.
5. Controllable parameters of interest for each component are listed as shown in Table 4.8. The system and its parameters are bolded and the assemblies and its parameters are italicized.

Table 4.8 Component, Controllable Parameters Template

Assembly, sub-assembly and components	Mass (grams)	Controllable parameters
1.1 Air transport assembly	*4701*	*Max air flow produced, max electrical draw, total volume, average density (4)*
1.1.1 Motor subassembly	3500	Max electrical power draw, max torque delivered, average density, depth, diameter (5)
1.1.2 Fan	700	Number of blades, depth, diameter, blade thickness, average density (5)
1.1.3 Counterweight	1	Solid volume, density (2)
1.1.4 Fan shroud	500	Depth, diameter, density (2)
1.2 Engine transport assembly	*16726*	*Max thermal power dissipation, max electrical power draw, total solid and liquid volume, average density (4)*
1.2.1 Thermostat	83	Solid volume, average density, open temperature (3)
1.2.2 Expansion tank subassembly	884	Solid volume, liquid volume, thickness, density (4)
1.2.3 Radiator cap	40	Solid volume, average density (2)
1.2.4 Radiator subassembly	5000	Solid volume, average density, liquid volume, depth front area, cooling fin area (6)
1.2.5 Left bracket	249	Solid volume, average density (2)
1.2.6 Right bracket	249	Solid volume, average density (2)
1.2.7 Inlet water hose	300	Thickness, average density, interior diameter, length (4)
1.2.8 Outlet water hose	300	Thickness, average density, interior diameter, length (4)
1.2.9 Temperature sensor	20	Solid volume, average density (2)

Table 4.8 Component, Controllable Parameters Template (Continued)

Assembly, sub-assembly and components	Mass (grams)	Controllable parameters
1.2.10 Water pump subassembly	4680	Max electrical power draw, max flow rate delivered, average density, depth, diameter (5)
1.2.11 Engine coolant	4921	Thermal capacitance, density (2)
1.3 Transmission oil assembly	*1598*	*Maximum thermal power dissipation, max electrical power draw, total solid & liquid volume, average density (4)*
1.3.1 Liquid-liquid heat exchanger subassembly	598	Solid volume, average density, liquid volume (3)
1.3.2 Transmission oil	1000	Thermal capacitance, density (2)
1.4 Refrigerant transport assembly	*4500*	*Max thermal power dissipation, total solid and liquid volume, average density (3)*
1.4.1 Drying container	300	Solid volume, average density, liquid volume (3)
1.4.2 Condenser subassembly	2200	Solid volume, average density, liquid volume, front area, cooling fin area (6)
1.4.3 Refrigerant	2000	Thermal capacitance as liquid, density as liquid, thermal capacitance as vapor, density as vapor (4)

Function Analysis:

6. From the physical system and using expert knowledge, and/or using the list of functional requirements, the functions of the existing system, assembly, sub-assembly and components are derived and listed.

7. The criticality of each function is described. High criticality implies that the function is critical or very important for the system to work properly; medium criticality implies that the function is somewhat important for the system to work properly; low criticality implies that the function is not important for the system to work properly. The criticality of each function listed is entered in the template.
8. **Solutions are identified by considering low-criticality components that could be removed or combined** as shown in the Table 4.9.

Table 4.9 Function Analysis Template

Function (s)	Criticality of items w.r.t functions	Criticality of function (s)	Solution ideas for combining or eliminating low criticality items
Transfer heat from engine, transmission system and cabin to atmosphere	High	High	
Channel air across the radiator	High	High	
Turn the fan when activated by the computer; signal from engine coolant assembly	medium	medium	Use a smaller, higher efficiency motor
Transport air across the engine transport assembly	medium	medium	Use a smaller fan that channels same amount of air
Balance the fan to prevent vibrations	high	low	Design fan accurately to avoid vibrations
Increase the volume of air that the fan can pull	moderate	low	Place fan in an appropriate place or modify the design of the fan (axial/radial fans) such that air flow rate is maximized
Remove heat from engine	High	High	
Allow engine coolant to pass through if above a certain temperature	medium	medium	
Store excess engine coolant	medium	medium	

Table 4.9 Function Analysis Template (Continued)

Function (s)	Criticality of items w.r.t functions	Criticality of function (s)	Solution ideas for combining or eliminating low criticality items
Prevent water from the radiator from flowing out	high	high	
transfer heat from the hot coolant to air	high	high	
Channel coolant	low	low	Water tight enclosures
Channel coolant	low	low	Add cooling fin area to fluid carrying components in order to reduce front area of the radiator
Channel coolant	low	high	
Channel coolant	low	high	
Send a signal to the computer indicating the engine coolant temperature	medium	medium	
Pump coolant	high	high	Use a smaller, higher efficiency pump
Store heat absorbed from the engine; prevent scale deposits in the cooling system; help lubricate water pump; prevent rust and corrosion in cooling system	high	high	
Remove heat from transmission	high	high	
Exchange heat from oil to coolant	high	high	
Store heat absorbed from the transmission	high	high	

Table 4.9 Function Analysis Template (Continued)

Function (s)	Criticality of items w.r.t functions	Criticality of function (s)	Solution ideas for combining or eliminating low criticality items
Remove heat from the cabin using refrigerant	High	High	
Store water trapped in the refrigerant transport assembly	moderate	low	
Store heat absorbed from the cabin	high	high	Targeted cabin cooling

8 solutions are generated using this step.

Working principles Analysis:

9. From the physical system and using expert knowledge, working principles for the existing system, assembly, sub-assembly and components are derived and listed.
10. **The alternate components that embody the existing working principles with potentially less mass than the existing components are identified**. Each alternate component is entered in the template.
11. **Alternate working principles for each existing working principle and alternate components embodying each alternate working principle are identified**. Each combination of alternate working principle and alternate component are entered in the template as shown in Table 4.10.

Table 4.10 Working Principle Analysis Template

Item	Existing working principle	Solutions based on existing working principles	Solutions based on alternate working principles
1. Cooling system	Forced transport	Natural convection	Thermo electric cooling (Peltier effect); convection, radiation
1.1 Air transport assembly	Forced transport		Use steam turbine to recover waste heat
1.1.1 Motor subassembly	Electric signal; force air	Brushless DC motor	Hydraulic motor; Motor driven by heat □ isual than electricity or pulleys
1.1.2 Fan	Force air	Series of small fans	Piezoelectric fans
1.1.3 Counterweight	Counterbalance		
1.2.2 Expansion tank subassembly	Closed container	Fluid bladder	
1.2.3 Radiator cap	Closed container	Seal	Valve
1.2.4 Radiator subassembly	Rigid connection	Micro scale radiators	
1.2.5 Left bracket	Rigid connection	Tubes	Rubber shock mounts
1.2.6 Right bracket	Rigid connection	Tubes	Rubber shock mounts
1.2.7 Inlet water hose	Tight connection		
1.2.8 Outlet water hose	Tight connection		
1.2.9 Temperature sensor	Electric signal	Thermometer, Thermistor sensor, Inductive proximity sensor	

Table 4.10 Working Principle Analysis Template (Continued)

Item	Existing working principle	Solutions based on existing working principles	Solutions based on alternate working principles
1.2.10 Water pump subassembly	Forced transport	DC motor	hydraulic pump
1.2.11 Engine coolant	Thermal capacitance	High performance coolant	Vaporized air
1.3 Transmission oil transport assembly	Forced transport		
1.3.1 Liquid-liquid heat exchanger subassembly	Thermal capacitance		
1.3.2 Transmission oil	Thermal capacitance	High performance oil	
1.4 Refrigerant transport assembly	Forced transport		
1.4.1 Drying container	Closed container	Fluid bladder	Bleed valve

32 solutions are generated using this step

Tests Analysis:

12. From the available documentation, system tests are identified and listed.
13. From the available documentation, and using expert knowledge, test measures for each system test are derived and listed as shown in Table 4.11.

Table 4.11 Test, Test Measures List

Tests	Test Measures
1. Wading depth test	Electrical damage, physical damage (2)
2. Acceleration test	Physical damage (1)
3. Vibration test	Excessive amplitudes, frequencies near natural frequencies (2)
4. Pressure swell test for ATF	Failure of any component in the transmission oil transport assembly (1)

Table 4.11 Test, Test Measures List (Continued)

Tests	Test Measures
5. Pressure swell test for coolant	Failure of any component in the engine coolant transport assembly (1)
6. Burst pressure test for ATF	Bursting of any component in the transmission oil transport assembly (1)
7. Burst pressure test for coolant	Bursting of any component in the engine coolant transport assembly (1)
8. Corrosion test	Presence of corrosion in any component (1)
9. Leak test	Presence of leaks from any component (1)
10. Heat transfer from engine test	Heat transferred from engine (1)
11. Heat transfer from transmission test	Heat transferred to / from transmission (1)
12. Heat transfer from cabin test	Heat transferred from cabin (1)
13. User safety test	Presence of sharp edges, presence of hot surfaces (2)

Matrix Analysis:

14. The function to component matrix is manually populated.

- **Consider combining components having similar functionalities**
- **Consider splitting components having multiple functionalities**

Functions are entered in the column heading of the function to component matrix. System, assemblies, and sub-assemblies / components are entered in the row heading. Interior of the matrix is populated by assigning a '1' to each relationship where a component serves a particular function and a '0' where a component does not serve a particular function. Solutions are identified by combining components that have similar functionalities and by splitting components that have multiple functionalities. Solution ideas are entered in the last column of the matrix. A sample of a function to component matrix is shown in the Figure 4.24.

Functions x Components Matrix	1.2.9 Temperature sensor	1.2.10 Water pump subassembly	1.2.11 Engine coolant	……	Sum	Solution Ideas
Turn the fan when activated by the computer; signal from refrigerant assembly	0	0	0	……….	1	
Allow engine coolant to pass through if above a certain temperature	0	0	0	……….	1	
Not allow engine coolant to pass through if below a certain temperature	0	0	0	……….	1	
Send a signal to the computer indicating the engine coolant temperature	1	0	0	……….	1	Integrate the signaling devices in the air transport assembly and the engine coolant transport assembly
Pump engine coolant through the engine coolant transport assembly	0	1	0	……….	1	Use the motor in the air transport assembly to perform the similar operation.
…………………..	…….	….	…….	…….	……	……………………..
Sum	1	2	4			

Figure 4.24 A Sample of a Function to Component Matrix

The other solutions that are generated using this step but not shown in the above matrix are:

- Ducting more outside air across the radiator and condenser to reduce the front area
- Using the car body to dissipate heat to the surrounding environment
- Using the fluid-carrying wheels as heat exchangers to convect heat to the air and conduct heat to the ground, to eliminate radiator, condenser and fan
- Integrating brackets with the radiator
- Insulating the engine cylinders
- Adding a chemical to increase the thermal capacitance of coolant and refrigerant in order to decrease front area of radiator, condenser and fan size.

8 solutions are generated using this step.

15. Manually populate the Requirements to Components matrix

- **Consider eliminating requirements related to a high number of components**
- **Consider satisfying requirements related to a high number of components using different functions, working principles, and / or components**
- **Consider modifying or eliminating components related to a low number of requirements**

Requirements are entered in the column heading of the requirements to components matrix. System, assemblies, and sub-assemblies / components are entered in the row heading. Interior of the matrix is populated by assigning a 1 to each relationship where a component serves to fulfill a particular requirement and a 0 where a component does not serve to fulfill a particular requirement. Solutions are identified by considering eliminating or relaxing requirements related to a high number of components, satisfying requirements related to a high number of components using different functions, working principles, or components and modifying or eliminating components related to a low number of requirements. Solution ideas are entered in the last column of the matrix. A sample of a requirement to component matrix is shown in Figure 4.25.

Requirements x Components	1.3.2 Transmission oil	1.4 Refrigerant transport assembly	1.4.1 Drying container	1.4.2 Condenser subassembly	1.4.3 Refrigerant	……………………	Sum	Observations
2.4 pass corrosion test without failure	0	1	1	1	0	……..	22	Use non-cooroding materials or protective layers like plastics such that they donot corrode
2.5 not fail under excess pressure	0	1	1	1	0	………	15	
3.1 not leak fluids into the environment	1	1	1	1	1	……..	18	Use leak-proof materials
4.1 prevent injuring the user	0	1	1	1	0	………..	22	Design parts such that they don't injure user
5.1 be secured to the vehicle frame	0	1	0	1	0	………	10	
…………………………………………	…….	………..	……….	……….	……….		……….	……………….
Sum	2	9	7	9	2	0		

Figure 4.25 A Sample of a Requirement to Component Matrix

3 solutions are generated using this step

16. Manually populate the controllable parameters to test measures matrix using the directions indicated in the template to populate the interior of the matrix.
    - **Identify single components parameters to change to reduce mass without negatively affecting test measures, by identifying rows in the controllable parameters to test measures matrix with all zeroes or all bright green cells**
    - **Identify groups of components parameters to change to reduce mass which have an overall net benefit or no negative affect on test measures, by identifying multiple rows in the controllable parameters to test measures matrix with bright green cells and purple cells that when combined would yield an overall net benefit or no negative effect on the test measures**

Tests and the test measures are entered in the first two row headings of the controllable parameters to test measures matrix. The third row of the matrix is populated by indicating the preferred outcome of each test measure. A '+1' is entered if more of the test measure is better, a '-1' if less of the test measure is better, or a '0' if the test measure should stay on target. The first column of the matrix is populated by indicating a direction to change each controllable parameter that would decrease the system mass. '+1' is entered if increasing the controllable parameter will lead to increase in system mass, a '-1' if decreasing the controllable parameter will lead to decreased system mass, or a '0' if a direction is not clear. Controllable parameters are entered in the second column of the matrix. The interior of the matrix is populated one row at a time by asking "if each controllable parameter is changed in the direction indicated (in the first column) to reduce mass, what will be the effect on each test measure?" '+1" is entered if the indicated change in the controllable parameter will have a positive effect on the test measure (in the same direction as the preferred direction indicated in the third row). '-1' is entered if the indicated change in the controllable parameter will have a negative effect on the test measure (opposite to the preferred direction indicated in the third row). '0' is entered if the indicated change in the controllable parameter will have no effect on the test measure, or if the effect is unclear. Individual and groups of controllable parameters that can be changed are identified to reduce mass without having negative effects on the test measures. Solution ideas are entered in the last column of the matrix. This procedure applied to a sample of the controllable parameter to test measure matrix is shown in Figure 4.26.

	"If the component parameter is changed in the direction indicated to reduce mass, what will be the effect on the test measure?" (+1 = T.M. increases, -1 = T.M. decreases, 0 = no effect or ambiguous effect on T.M.) ø	Electrical damage	Physical damage	Vibration amplitude	……………	Sum	%	Observations
Direction to change Cpt. Param. to decrease mass (+1 = up, -1 = down, 0 = unclear)	Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target)	-1	-1	-1	…			
-1	Inner diameter	0	0	0	……	0	0%	Shape optimization of all components; Make hoses shorter
-1	Solid Volume	0	1	1	……	4	2%	Make hoses smaller diameter
-1	Liquid volume	0	0	1	….	5	3%	
-1	Density	0	0	1	…..	2	1%	Reduce mass of all components by using lower density materials of equal or better strength
……	……………	…..	…..	……	……	…….	…….	………
	Sum	1	18	53		188	1	

Figure 4.26 A Sample of Controllable Parameter to Test Measure Matrix

The other solutions that are generated using this step but not shown in the above matrix are:

- Directing more air across the cooling surfaces
- Increasing the cooling fin area and decrease the front area
- Increasing the flow rate of coolant & oil (and air) in order to decrease the front area of the radiator, condenser and fan size
- Seeking a better performing coolant & oil
- Seeking a better performing refrigerant

9 solutions are generated using this step.

It could also be noted that the solutions that were generated using the comprehensive method are recovered using the M^5 method along with handful of additional solutions. 63 solutions are generated using the M^5 method when compared to 25 solutions generated using the comprehensive method. The M^5 method was applied to the BMW series 1 seat in a group setting and 137 solutions were generated in the course of two afternoons.

The comprehensive method and the M^5 method were used to generate solutions at the component or lowest level of the hierarchy of the system being considered. This approach is natural and valuable, but it is strongly affected by the existing solutions. As such, the design freedom may not be extensive as the one a designer would have if the system is considered at the assembly or sub-assembly levels. Next chapter focuses on this aspect.

CHAPTER 5

DEVELOPMENT OF A SYSTEMATIC METHOD FOR ASSEMBLY LEVEL ANALYSIS

5.1 Introduction

Using the relationships between the rows and columns of matrices, the systematic method developed and described in the previous chapter helps to generate solutions at the lowest level of the hierarchy, i.e., at the component level. The entities in the primary level matrices of the modeling scheme are elicited in a hierarchical manner. Thus solutions could be generated at the system or sub-system levels of the hierarchy. Therefore, a method to generate solutions at a higher level in the hierarchy should be investigated. It would be interesting to analyze if, based on such an approach, additional solutions (different from those generated at the lowest level of the hierarchy) could be generated at a higher level of the hierarchy to support the premise discussed in the last chapter that the design freedom is larger. This chapter presents a methodology to transfer lowest component information to higher levels in order to support an approach to investigate mass savings at system or subsystem levels.

5.2 Hierarchical Decomposition and Re-composition

As various sub-assemblies usually include an unequal number of components and functions, some way to compare them has to be established. In order to analyze various assemblies, information gained at the component level could be combined and transformed to a higher level in the hierarchy. At the lowest level, each cell represents a binary correlation between the entities in the row headers and those in the column headers of a matrix. A common way of comparison could be established by finding how many cells indicate a correlation between the rows and columns of an assembly. To establish this comparison, two arbitrary matrices are considered as shown in Figure 5.1. Matrix 1 has 5 entities in the row headings (A to E) and 6 entities (AA to FF) in the column headings. Matrix 2 has 8 entities in the row headings (A to H) and 7 entities (AB to GH) in the column headings. Positive correlations between column and row headers are indicated by a 1 in the corresponding cells, and the sum (9) of the two matrices is the same. Observing this sum, one could conclude that the correlation strengths of both matrices are the same. But, this conclusion is correct only if both matrices have equal number of rows and columns. As the matrices usually have unequal number of rows and columns, this conclusion does not hold. Therefore, a common way to represent the 'degree of interaction' in the matrix has to be established.

	AA	BB	CC	DD	EE	FF	Sum
A	1	0	0	0	0	0	1
B	1	0	1	1	0	0	3
C	0	1	1	0	1	0	3
D	0	0	1	0	0	0	1
E	0	0	0	1	0	0	1
Sum	2	1	3	2	1	0	**9**

Matrix 1
Number of rows: 5
Number of columns: 6

	AB	BC	CD	DE	EF	FG	GH	Sum
A	1	0	0	0	0	0	0	1
B	1	0	0	1	0	0	0	2
C	0	1	0	0	0	0	0	1
D	0	0	1	0	0	0	0	1
E	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0
G	0	0	0	1	0	1	0	2
H	0	0	1	1	0	0	0	2
Sum	2	1	2	3	0	1	0	**9**

Matrix 2
Number of rows: 8
Number of columns: 7

Figure 5.1 Two Arbitrary Matrices with Unequal Number of Rows and Columns

It could be observed that there is one empty column in matrix 1 (FF) and two empty columns and rows in matrix 2 (E, F, EF, GF). Though a common way to represent the degree of interaction could be established, it might not consider the presence or absence of empty columns or the diagonalization aspect in a matrix, which is supposedly an important metric according to Axiomatic Design [45]. In other words, the ‘structure of interaction’ should also be considered to compare the matrices. So, in order to transfer the information from the lower level of the hierarchy to a level above, a mapping option should be established that captures both the degree and structure of interaction of a matrix.

Various mapping options are investigated to represent the degree and structure of interaction in the matrix. They are discussed below.

1. Sum: The sum is obtained by calculating the total number of interactions in a matrix as shown in Figure 5.2.

Sum of matrix 1 = 9; Sum of matrix 2 = 9

<table>
<tr><th></th><th>AA</th><th>BB</th><th>CC</th><th>DD</th><th>EE</th><th>FF</th></tr>
<tr><td>A</td><td colspan="6" rowspan="5">Sum = 9</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td></tr>
<tr><td>D</td></tr>
<tr><td>E</td></tr>
</table>

<table>
<tr><th></th><th>AB</th><th>BC</th><th>CD</th><th>DE</th><th>EF</th><th>FG</th><th>GH</th></tr>
<tr><td>A</td><td colspan="7" rowspan="8">Sum = 9</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td></tr>
<tr><td>D</td></tr>
<tr><td>E</td></tr>
<tr><td>F</td></tr>
<tr><td>G</td></tr>
<tr><td>H</td></tr>
</table>

Figure 5.2 Mapping Option #1 Applied to Matrices 1 and 2

This metric is not sufficient since it does not take into account the variable sizes of the matrices being captured.

2. Percentage: The percentage is obtained by dividing the total number of interactions by the total number of rows and columns in a matrix as shown in Figure 5.3.

Percentage of matrix 1 = 9 / (5*6) = 0.3; Percentage of matrix 2 = 9 / (8*7) = 0.16

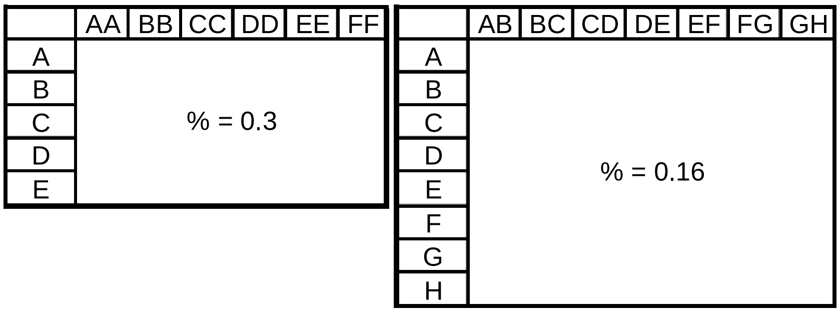


Figure 5.3 Mapping Option #2 Applied to Matrices 1 and 2

This metric seems to give a more accurate view of the degree of interaction the matrices.

3. Range with weighting: The range of a matrix may be obtained by categorizing the percentage metric of a matrix into a range specified by the user. If % of a matrix is from 0.1 to 0.25 then the "range" is 1, 0.26 to 0.5 then "range" is 3 and 0.51 to 1.0 then the range is "9". The 1, 3, 9 range metric is chosen because it is a common and accepted approach in the house of quality [31]. Applying this range, weight of matrix 1 (with % = 0.3) is 3 and weight of matrix 2 (with % = 0.16) is 1 as shown in Figure 5.4.

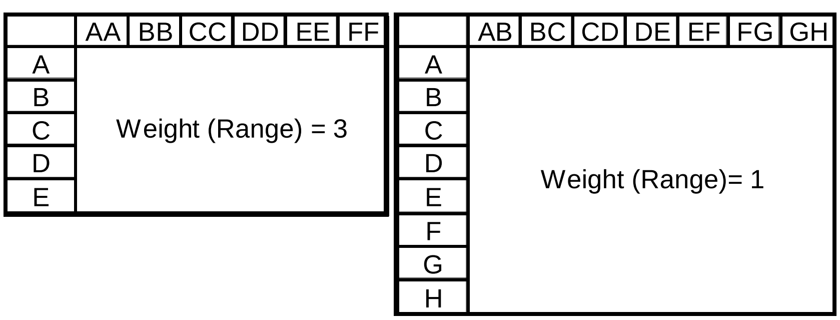


Figure 5.4 Mapping Option #3 Applied to Matrices 1 and 2

From the above three mapping options, one can infer that sum does not provide an accurate difference in the degree of interaction. It implies that matrices 1 and 2 are equal in degree of interaction. Third mapping option, i.e., range with mappings shows a more meaningful result, but one can easily observe that if the number of interactions been reduced by 2, the numbers obtained would have been 7 / (5 * 6) = 0.2333 which corresponds to a “1” and 7 / (8 * 7) = 0.125, also corresponding to a “1”. Thus the range with weighting does not show a meaningful relationship. The second mapping option i.e., percentage, effectively captures the degree of interaction as it shows the accurate difference in the degree of interaction for the unequal numbers of rows and columns. Hence, percentage (mapping option #2) is selected to represent the degree of interaction. The above discussed mapping options do not represent the “structure of interaction” in a matrix and other mapping options must be considered to represent the structure. These are presented next.

Matrices can be manipulated by swapping rows or columns to check the diagonalization aspect in it. The Axiomatic Design approach to the independence axiom [45] shows how this is done to evaluate coupled, decoupled or uncoupled relations. Decision matrices in the axiomatic design approach relate functional requirements to design parameters and the uncoupled mapping which is illustrated by a diagonal relations matrix are considered the ideal one. The next best relation is the decoupled one where the matrix is lower triangular meaning that functions can be accomplished in a specific order to avoid iterations. Therefore, examining our relation matrices, we need to see if these matrices become uncoupled or decoupled. One possible indication is the number of empty rows or columns in the relation matrix. Therefore the next metrics examined consider this indicator in a variety of ways.

4. Logical ON/OFF (0-1): When a matrix has one or many empty rows / columns, then a “1” is denoted in the matrix. Else a “0” is given. Since matrix 1 has 1 empty column and matrix 2 has 2 empty rows and 2 empty columns, both matrices 1 and 2 gets a “1” as shown in Figure 5.5

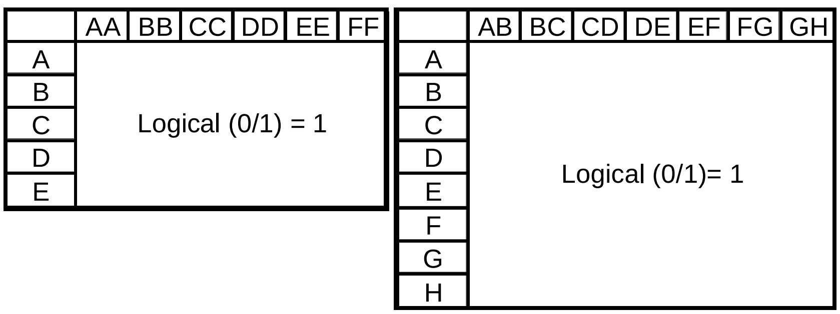


Figure 5.5 Mapping Option #4 Applied to Matrices 1 and 2

This is not a potential mapping option to represent the structure of interaction because it does not represent any useful differentiating result.

5. Logical ON/OFF Row Check (0-1): When a matrix has one or many empty rows, then a “1” is denoted in the matrix else a “0” is given. Since matrix 1 has no empty rows and matrix 2 has 2 empty rows, matrix 1 gets “0” and matrix 2 gets a “1” as shown in Figure 5.6

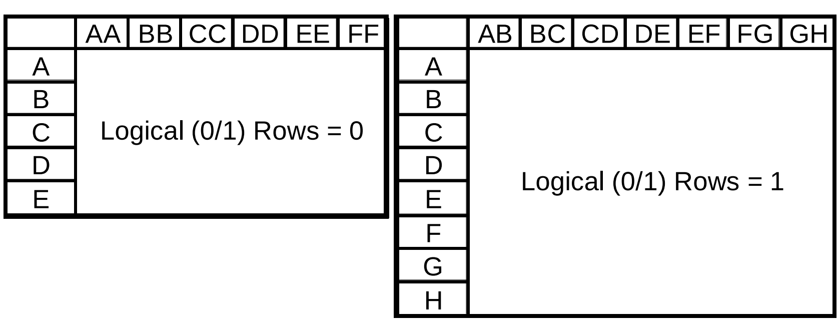


Figure 5.6 Mapping Option #5 Applied to Matrices 1 and 2

This mapping option is considered to analyze the impact of the entities in the row only. But, this is not a potential mapping option to represent the structure of interaction because it does not consider the columns of a matrix.

6. Logical ON/OFF Column Check (0-1): When a matrix has one or many empty columns, then "1" is denoted in the matrix else "0" is denoted. Since matrix 1 has 1 empty column and matrix 2 has 2 empty columns, both matrices 1 and 2 get "1" as shown in Figure 5.7.

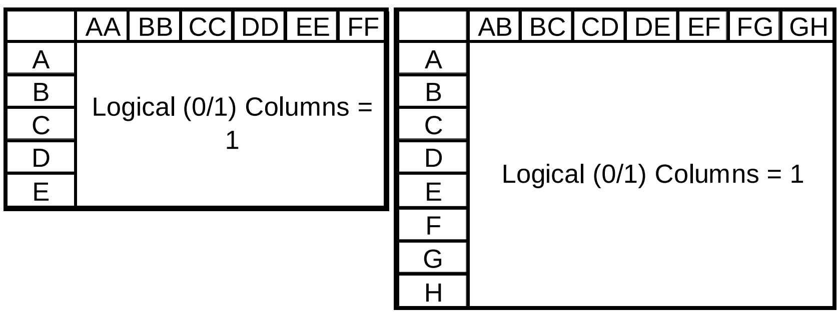


Figure 5.7 Mapping Option #6 Applied to Matrices 1 and 2

This mapping option is considered to analyze the impact of the entities in the column only. But, this is not a potential mapping option to represent the structure of interaction because it does not consider the rows of a matrix and the total number of empty columns.

7. Sum (Logical ON/OFF Row Check (0-1)): This mapping option represents the total number of empty rows in a matrix. Since matrix 1 has no empty rows and matrix 2 has 2 empty rows, matrix 1 gets a "0" and matrix 2 gets "2" as shown in figure 5.8

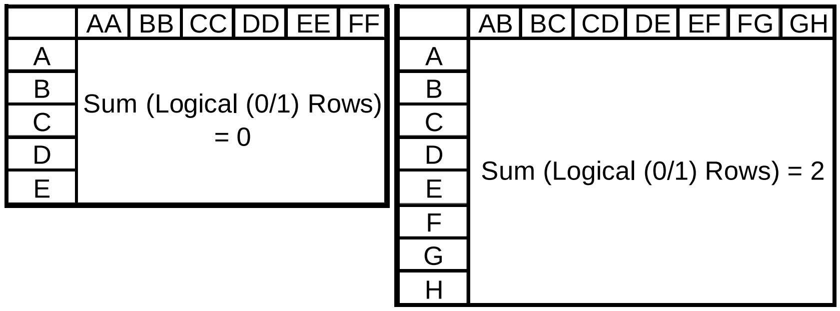


Figure 5.8 Mapping Option #7 Applied to Matrices 1 and 2

Though this mapping option represents the total number of empty rows in a matrix, it is not a potential mapping option to represent the structure of interaction because it does not consider the columns of a matrix.

8. Sum (Logical ON/OFF Column Check (0-1)): This mapping option represents the total number of empty columns in a matrix. Since matrix 1 has 1 empty column and matrix 2 has 2 empty rows, matrix 1 gets "1" and matrix 2 gets "2" as shown in figure 5.9

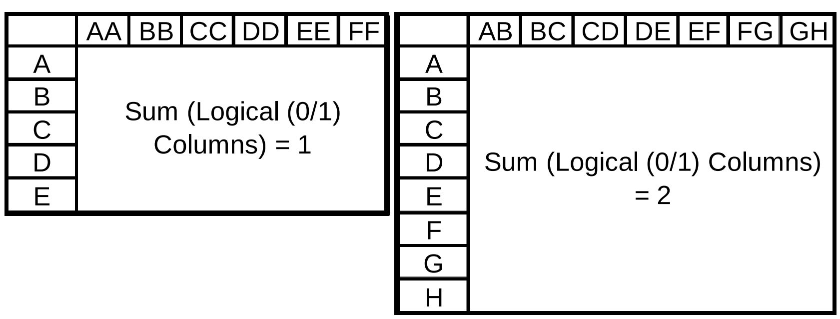


Figure 5.9 Mapping Option #8 Applied to Matrices 1 and 2

Though this mapping option represents the total number of empty columns in a matrix, it is not a potential mapping option to represent the structure of interaction because it does not consider the rows of a matrix.

9. Percentage (Logical ON/OFF Row Check (0-1)): This mapping option represents the percentage of empty rows in a matrix. Percentage of empty rows is obtained by dividing the number of empty rows in a matrix by the total number of rows in the

same matrix. Since matrix 1 has 5 rows and no empty rows, the value is 0 / 5 = 0 and matrix 2 has 8 rows and 2 empty rows, the value is 2/8 = 0.25 as shown in figure 5.10.

	AA	BB	CC	DD	EE	FF
A	% (Logical (0/1) Rows) = 0					
B						
C						
D						
E						

	AB	BC	CD	DE	EF	FG	GH
A	% (Logical (0/1) Rows) = 0.25						
B							
C							
D							
E							
F							
G							
H							

Figure 5.10 Mapping Option #9 Applied to Matrices 1 and 2

Though this mapping option represents the percentage of empty rows in a matrix, it is not a potential mapping option to represent the structure of interaction because it does not consider the columns of a matrix.

10. Percentage (Logical ON/OFF Column Check (0-1)): This mapping option represents the percentage of empty columns in a matrix. Percentage of empty columns is obtained by dividing the number of empty columns in a matrix by the total number of columns in the same matrix. Since matrix 1 has 6 columns and one empty column, the value is 1 / 6 = 0.167 and matrix 2 has 7 columns and 2 empty columns, the value is 2/7 = 0.285 as shown in figure 5.11.

	AA	BB	CC	DD	EE	FF
A	% (Logical (0/1) Columns) = 0.167					
B						
C						
D						
E						

	AB	BC	CD	DE	EF	FG	GH
A	% (Logical (0/1) Columns) = 0.285						
B							
C							
D							
E							
F							
G							
H							

Figure 5.11 Mapping Option #10 Applied to Matrices 1 and 2

Though this mapping option represents the percentage of empty columns in a matrix, it is not a potential mapping option to represent the structure of interaction because it does not consider the rows of a matrix.

11. Product of percentage of logical row and column: Mapping options 9 and 10 considered either the percentage of row or column but not both. This mapping option represents the product of the percentage of empty rows and columns in a matrix and can be obtained by multiplying the values of the matrices obtained by using mapping options 9 and 10. Therefore, using this mapping option, matrix 1 is represented by 0 * 0.167 = 0 and matrix 2 is represented by 0.25 * 0.285 = 0.071 as shown in figure 5.12.

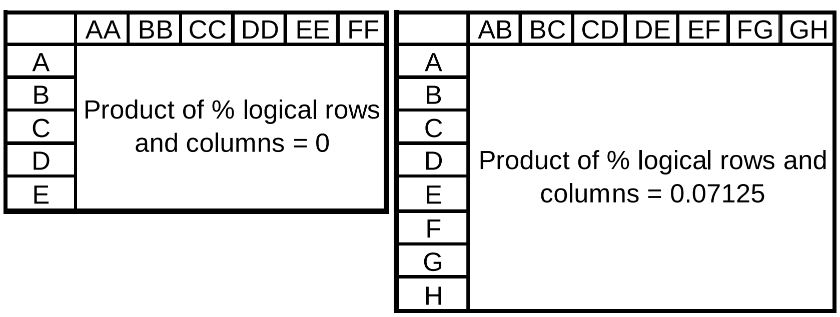


Figure 5.12 Mapping Option #11 Applied to Matrices 1 and 2

The presence of empty rows or columns turns the logical check to zero. So, the product of zero with any other number results in zero as it happened for matrix 1 shown in figure 5.12. Hence, this is not an ideal mapping option to represent the structure of interaction.

12. Sum of logical 0/1's in rows AND columns divided by the product of total number of rows and columns: This mapping option is obtained by dividing the total number of rows and columns that has at least one correlation in them by the product of total number of rows and columns in a matrix. Therefore, using this mapping

option, matrix 1 is represented by (5+5) / (5*6) = 0.333 and matrix 2 is represented by (6+5) * (8*7) = 0.1964 as shown in figure 5.13.

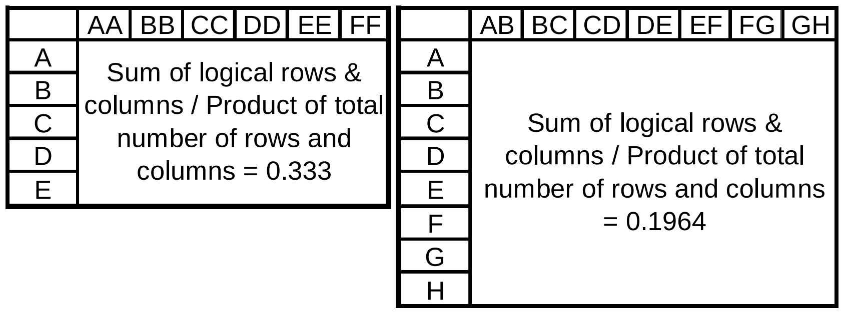


Figure 5.13 Mapping Option #12 Applied to Matrices 1 and 2

This seems to be a potential mapping option because it considers the presence/absence of both rows and columns in a matrix and also the total number of rows and columns in a matrix.

13. Sum of logical 0/1's in rows AND columns divided by sum of total number of rows and columns: This mapping option is obtained by dividing the total number of rows and columns that have at least one correlation in them by the total number of rows plus columns in a matrix. Therefore, using this mapping option, matrix 1 is represented by (5+5) / (5+6) = 0.91 and matrix 2 is represented by (6+5) / (8+7) = 0.733 as shown in figure 5.14.

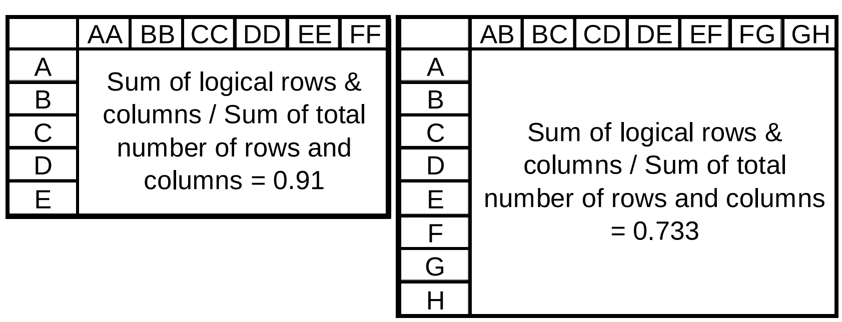


Figure 5.14 Mapping Option #13 Applied to Matrices 1 and 2

This mapping option also seems to be a potential mapping option because it considers the presence/absence of both rows and columns in a matrix and the total number of rows and columns in a matrix. Mapping options #12 and #13 differ due to the difference in their denominator. Sum of rows and columns in a matrix represents a total but product of rows and columns does not do so. As dividing the numerator by a total is more meaningful when compared to the product, mapping option #13 is chosen to represent the structure of interaction. Hence, this mapping option could be used as a common way to compare the structure of interaction in the matrices with equal and unequal number of empty rows and columns.

From the above discussed mapping options, it could be inferred that none of the mapping option have the capability to represent both degree and structure of the matrix. Product or Sum of mapping option #2 and mapping option #13 could be used to represent both degree and structure of interaction as a single metric. Doing so does not yield a concrete form of representation in a matrix because the product/sum of the mapping options 2 and 13 does not differentiate the degree and structure of interaction. Hence, it is decided to represent the degree and structure of interaction of the matrix using two metrics M1 and M2 respectively. To summarize, M1 and M2 are given below.

M1 (Mapping option #2) – The degree of interaction is obtained by computing a correlation percentage in a matrix, which is obtained by dividing the number of correlations in a matrix by the product of the rows and columns in the matrix. The matrix represents a subsystem.

M2 (Mapping option #13) – The structure of interaction in a matrix is obtained by dividing the number of rows and columns that have at least one correlation by the total number of rows plus columns in a matrix.

Thus, the information at the lower level of the hierarchy is transferred to a level above the hierarchy using metrics M1 and M2. This answers the research question 2.1. M1 and M2 can be represented as decimal values or as percentages. If M1 = 0% or 0, then there is no correlation in the matrix. If M1 = 100% or 1, then all the entities in the matrix are correlated to each other. If M2 = 100% or 1, then there are no empty rows or columns. Conversely, if M2 = 0% or 0, then the matrix is empty i.e., no relation exists between any entities in the matrix.

Diagonalization:

As diagonalization occurs in a square matrix, the number of rows (Nr) is equal to number of columns (Nc). In other words, Nr = Nc = N. If metric M1 is equal to 1/N and metric M2 is 1 (no empty rows or columns), then the matrix is a diagonal matrix. To explain this, an arbitrary matrix is considered as shown in Figure 5.15 (a). This square matrix has equal number of rows and columns (Nc = Nr = 5). Applying the metrics M1 and M2 to this matrix we get: M1 = 5 / (5*5) = 1 / 5 = 1 / N = 0.2 and M2 = (5+5) / (5+5) = 1 as shown in Figure 5.15 (b), which falls into the criteria imposed for diagonalization. Thus, the aspect of diagonalization is captured by using metrics M1 and M2.

	A	B	C	D	E
A	1	0	0	0	0
B	0	1	0	0	0
C	0	0	1	0	0
D	0	0	0	1	0
E	0	0	0	0	1

(a)

	A	B	C	D	E
A					
B					
C	M1 = 0.2; M2 = 1				
D					
E					

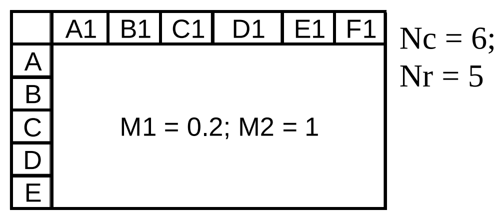
(b)

Figure 5.15 (a): An Arbitrary Square Matrix; (b): Using Metrics to the Matrix

If the matrix is not a square matrix and if M1 >= 1/Nr, M2 = 1 and if Nc > Nr then some entities in the rows of a matrix are correlated to multiple entities in the columns of the same matrix. This condition is explained in the example given below. Consider a matrix as shown in Figure 5.16 (a). In this matrix, Nc >Nr and the entity B in the row is related to B1 and F1 (entities in the columns) in the matrix. Applying the metrics to this matrix: M1 = 0.2 and M2 = 1 as shown in Figure 16 (b). One can infer that this example satisfies the criteria M1 >= 1/Nr (0.2), M2 = 1 and Nc > Nr thereby representing the fact that some entities in the rows of the matrix are correlated to multiple entities in the columns of the same matrix.

	A1	B1	C1	D1	E1	F1
A	1	0	0	0	0	0
B	0	1	0	0	0	1
C	0	0	1	0	0	0
D	0	0	0	1	0	0
E	0	0	0	0	1	0

(a)



(b)

Figure 5.16 (a): An Arbitrary Matrix with Nc > Nr; (b): Using Metrics to the Matrix

If M1 >= 1/Nc, M2 = 1 and if Nr < Nc then some entities in the columns of a matrix are correlated to multiple entities in the rows of the same matrix. This condition is explained in the example given below. Consider a matrix as shown in Figure 5.17 (a). In this matrix, Nr >Nc and the entity A1 in the column is related to rows A and E, and entity B1 is related to rows B and F in the matrix. Applying the metrics to this matrix: M1 = 0.233 and M2 = 1 as shown in Figure 17 (b). One can infer that this example satisfies the criteria M1 >= 1/Nc (0.2), M2 = 1 and if Nr < Nc thereby representing the fact that some entities in the columns of a matrix are correlated to multiple entities in the rows of the same matrix.

	A1	B1	C1	D1	E1
A	1	0	0	0	0
B	0	1	0	0	0
C	0	0	1	0	0
D	0	0	0	1	0
E	1	0	0	0	1
F	0	1	0	0	0

(a)

<table>
<tr><th></th><th>A1</th><th>B1</th><th>C1</th><th>D1</th><th>E1</th></tr>
<tr><td>A</td><td colspan="5" rowspan="6">M1 = 0.2333; M2 = 1</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td></tr>
<tr><td>D</td></tr>
<tr><td>E</td></tr>
<tr><td>F</td></tr>
</table>

Nr = 6;
Nc = 5

(b)

Figure 5.17 (a): An Arbitrary Matrix with Nr > Nc; (b): Using Metrics to the Matrix

If M2 < 1 one should first perform a consistency check in order to crosscheck if the matrix has been populated correctly or not. If M2<1 then some entities in a column are not related to any entity in any row of the same matrix and / or vice versa.

The metrics M1 and M2 are applied to a sample of a manually populated function to component matrix as shown in Figure 5.18.

Functions to Components matrix		1.1 Air transport assembly				1.2 Engine coolant transport assembly										
		1.1.1 Motor sub-assembly	1.1.2 Fan	1.1.3 Shroud	1.1.4 Fan Shroud	1.2.1 Thermostat	1.2.2 Expansion tank sub-assembly	1.2.3 Radiator cap	1.2.4 Radiator sub-assembly	1.2.5 Left bracket	1.2.6 Right bracket	1.2.7 Inner water hose	1.2.8 Outer water hose	1.2.9 Temperature sensor	1.2.10 Pump sub-assembly	1.2.11 Engine Coolant
1.1 maintain engine temperature within operating range	1.1.1.1 Turn the fan when activated by the computer	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1.1.2.1 Allow engine coolant to pass through if above a certain temperature	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	1.1.2.4 Pump engine coolant through the engine coolant transport assembly	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	1.1.3.1 Store heat absorbed from the engine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	1.1.4.1 store excess engine coolant	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	1.1.4.2 Pump engine coolant through the engine coolant transport assembly	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	1.1.5 allow engine coolant to be added	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0

Air transport assembly:
Nr = 10; Nc = 4;
M1 = 1/ (10 *4) = 0.025;
M2 = ((1+1) / (10+4)) = 0.142;

Engine transport assembly:
Nr = 10; Nc = 11;
M1 = 9/ (10*11) = 0.0818;
M2 = (9+7) / (10+11) = 0.7619

Figure 5.18 Mapping Options Applied to a Sample of the Function x Components Matrix of the Cooling System

5.3 Development of a Systematic Method for Assembly Level Analysis

Using the two metrics M1 and M2, a common way to compare various sub-systems irrespective of the unequal number of rows and columns is established. A systematic method is developed to generate solutions at a higher level of the hierarchy. Steps in the systematic method are given below. Those that aid the designer to generate solutions are in bold italics.

Phase 1: Populating the matrices in the model:

1. Enter the entities of the domains in the primary level matrices with at least two levels of hierarchy.
2. Manually populate the primary level matrices at the lowest level of the hierarchy (typically component level).

Phase 2: Consistency check:

3. Obtain the automatically generated functions to components matrix by multiplying the corresponding primary level matrices, namely, functions to working principles matrix and working principles to components matrix.
4. Manually populate the function to component matrix at the lowest level of hierarchy.
5. Obtain a consistent function x component matrix by comparing the manually populated and the automatically generated function x component matrices and eliminating the inconsistencies.

Phase 3: Hierarchical re-composition and analysis:

6. Use metrics M1 and M2 to transform the information obtained at the lowest level of hierarchy to a level above.
7. Prioritize the assemblies' related to the higher level functions in the descending order of the metric M1 value.
8. Using the metrics M1 and M2, interpret the correlation between the assembly and the assembly level functions.

   -If an assembly is not related to any assembly level function or vice versa (represented by M2 = 0 across assemblies and the assembly level functions), then the assembly does not serve any purpose and it can be potentially removed.

Phase 4: Function – Working principle analysis:

9. Analyze the assembly level functionalities.
    - ***Integrate the assemblies that have similar functionalities***. Output list.
10. Determine the working principle of an existing assembly.
    - ***Find alternate assemblies that embody the same working principle of the existing assembly / target system.*** Output list.
11. Determine an alternate working principle of an existing assembly
    - ***Find alternate assemblies that embody the alternate working principle of the existing assembly / target system.*** Output list.

Phase 5: Feasibility study:

12. Sort out feasible solutions by conducting a feasibility study on the list of solutions generated in phase 4.
13. List the feasible solutions and propose solutions for future development.

5.4 Case Study: BMW Z4 Cooling System

A case study is performed to validate the steps proposed in the systematic method for sub-system analysis discussed in the previous sub-section. To compare the solutions generated using the systematic method for assembly level analysis with those generated with the systematic method for component level analysis (in chapter 4), the BMW Z4 cooling system is again used to conduct the case study. The phases in the systematic method are executed in order.

Phase1: Populating the matrices in the model:

The entities of the domains in the primary level matrices are entered with at least two levels of hierarchy and manually populated at the lowest level of hierarchy using a quantitative 0-1 numbering scheme as discussed in Chapter 3, sub-section 3.3.1.

Phase 2: Consistency check:

The functions to components matrix is obtained by multiplying the corresponding primary level matrices, namely, functions to working principles matrix and working principles to components matrix. The functions to components matrix is automatically generated by matrix multiplication in the Excel sheet. As discussed in sub-section 3.3.2, consistency check is performed on the functions to components matrix by finding the false positives and false negatives and by observing if any real relationship are missed in the corresponding primary level matrices. A sample of the functions to components matrix obtained after consistency check is shown in Figure 5.19.

Functions to Assemblies matrix		1.1 Air transport assembly				1.2 Engine coolant transport assembly										
		1.1.1 Motor sub-assembly	1.1.2 Fan	1.1.3 Shroud	1.1.4 Fan Shroud	1.2.1 Thermostat	1.2.2 Expansion tank sub-assembly	1.2.3 Radiator cap	1.2.4 Radiator sub-assembly	1.2.5 Left bracket	1.2.6 Right bracket	1.2.7 Inner water hose	1.2.8 Outer water hose	1.2.9 Temperature sensor	1.2.10 Pump sub-assembly	1.2.11 Engine Coolant
1.1 maintain engine temperature within operating range	1.1.1.1 Turn the fan when activated by the computer	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1.1.2.1 Allow engine coolant to pass through if above a certain temperature	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	1.1.2.4 Pump engine coolant through the engine coolant transport assembly	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	1.1.3.1 Store heat absorbed from the engine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	1.1.4.1 store excess engine coolant	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	1.1.4.2 Pump engine coolant through the engine coolant transport assembly	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	1.1.5 allow engine coolant to be added	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0

Figure 5.19 A Sample of the Functions to Components Matrix Obtained After Consistency Check

Phase 3: Hierarchical re-composition and analysis:

The correlation between the entities at the lowest level of the hierarchy are transferred to a level above using the metrics M1 and M2 as shown in Figure 5.24.

Functions to Assemblies matrix	1.1 Air transport assembly	1.2 Engine coolant transport assembly	1.3 Transmission oil transport assembly	1.4 Refrigerant transport assembly
1.1 maintain engine temperature within operating range	M1 = 0.025; M2 = 0.142	M1 = 0.0818; M2 = 0.7619	M1 = 0; M2 = 0	M1 = 0; M2 = 0
1.2 maintain transmission temperature within operating range	M1 = 0; M2 = 0	M1 = 0.030303; M2 = 0.142	M1 = 0.5; M2 = 1	M1 = 0; M2 = 0
1.3 maintain cabin temperature within comfort range	M1 = 0.0833; M2 = 0.1428	M1 = 0; M2 = 0	M1 = 0; M2 = 0	M1 = 0.222; M2 = 0.666

Figure 5.20 Hierarchical Re-composition of Functions to Components Matrix Using Metrics M1 and M2

Using the metric M1, the assemblies are prioritized with respect to the degree of interaction in an assembly. In the above functions to components matrix of a cooling system, transmission oil transport assembly has the highest degree of correlation when compared to other assemblies. Using M1, the function-assembly interaction is prioritized in the descending order of M1. They are prioritized as follows (F represents a function and A represents an assembly):

1. F1.2 – A1.3
2. F1.3 – A1.4
3. F1.3 – A1.1
4. F1.1 – A1.2
5. F1.2 – A1.2
6. F1.1 – A1.1

This prioritization allows the user to analyze the degree of interaction of a particular assembly – function coupling with the other one, thus acting as an attention directing metric. Using the metrics M1 and M2, the correlation between each assembly and the assembly level function is interpreted and the following observations are made.

Function “Maintain engine temperature within operating range”

– is accomplished at the top level by: Engine coolant transport assembly and then by air transport assembly.
– has no correlation with the transmission oil and refrigerant transport assemblies

Function “Maintain transmission temperature within operating range”

– is accomplished by the transmission oil assembly and engine coolant transport assembly.

– is not accomplished by the air transport or refrigerant transport assemblies.

Function “Maintain cabin temperature within comfort range”

– is accomplished by: refrigerant transport assembly and then by air transport assembly

– has no visible correlation with the engine coolant transport or transmission oil transport assembly

The air transport assembly is related to the functions in the following prioritization:

– Maintain cabin temperature within comfort range

– Maintain engine temperature within operating range

It is not related to maintain transmission temperature within operating range.

The engine coolant transport assembly is related only to the functions in the following prioritization:

- Maintain engine temperature within operating range

- Maintain transmission temperature within operating range

It is not related to maintain cabin temperature within operating range.

The transmission oil transport assembly is related only to the function “maintain transmission temperature within operating range” and is not related to any other high level functions. The refrigerant transport assembly is related only to the function “maintain cabin temperature within comfort range” and not related to other higher level functions.

Observation: Since, all assemblies are related to at least one assembly level function and vice versa, no assemblies could be removed using this solution strategy.

Phase 4: Function – Working principle analysis:

The assembly level functionalities are analyzed. The functional hierarchy is studied to integrate the functions that have similar functionalities as shown in the functional analysis Table (Table 5.1).

Table 5.1 Integrating the Assemblies that have Similar Functionalities

Functions at the System level	**Re-interpreting the System level functions**	**Decomposing the system level functions to sub-system level functions**	**Main Components / sub-assemblies involved in performing the sub-system and system level functions**	**Assembly that performs the functions**
1.1 Maintain engine temperature within operating range	1.1 Remove heat from the engine	1.1.1: Circulate the fluid	Motor, pipes/tubes, temperature sensor	Air transport assembly (A1) and Engine coolant transport assembly (A2)
		1.1.2: Take heat from the engine	Coolant,	
		1.1.3: Transfer heat	**Fan sub-assembly,** radiator	
1.2 Maintain transmission temperature within operating range	1.2 Remove heat from the transmission	1.2.1: Circulate the fluid	Motor, pipes/tubes.	Engine coolant transport assembly (A2) and Transmission oil assembly (A3)
		1.2.2: Take heat from the transmission	Transmission oil	
		1.2.3: Transfer heat	Liquid-Liquid heat exchanger	
.3 Maintain cabin temperature within comfort range	1.3 Remove heat from the cabin	1.3.1: Circulate the fluid	Motor, pipes	Air transport assembly (A1) and Refrigerant transport assembly (A4)
		1.3.2: Take heat from the cabin	Refrigerant	
		1.3.3: Transfer heat	**Fan sub-assembly,** condenser	

The system level functionalities are analyzed for functional integration. For example, the three system level functionalities perform similar function, i.e., maintaining a particular system within operating range but use different sub-assemblies to perform the function. So, a solution that might arise from this analysis is to have a single system with minimal components that maintains various systems within operating range instead of having multiple systems with many components. But, this observation is quite vague. So, the top level (system level) functionality is reinterpreted and then decomposed to sub-system level functionalities to analyze the functional integration more clearly. From Table 5.3, one can find that the nature of the sub-system level function is similar but they are accomplished by various sub-assemblies. There are three similar sub-system functions i.e., circulate a fluid, remove the heat from the system and transfer the heat. It is interesting to note that functions 1.1.3 and 1.3.3, i.e., transferring heat carried by the fluid to the atmosphere is accomplished by the same fan sub-assembly but uses different heat exchangers (radiator and condenser). Also, the function 1.2.3 uses another heat exchanger (liquid-liquid heat exchanger). Hence, using the assembly integration strategy, a solution could be to use the same heat exchanger to transfer heat from all the circulating fluids. It can be observed that the function circulating the fluid in the three sub-systems is carried out by three different motors and piping systems. Hence, using the assembly integration strategy again, a solution that arises from this analysis is to use the same motor to circulate the fluid. Also, three different fluids are used to remove heat from different systems thereby contributing to approximately 30% of the cooling system's mass. If the same fluid is used to remove heat from different systems, then it might save mass and also eliminate various piping systems and dedicated motors that are used for circulating different fluids. Hence, using this solution step, the following solutions are generated by the sub-system functional analysis:

1. Use same fluid to remove heat from engine, transmission and cabin of an automobile
2. Use same heat exchanger to transfer heat from the three fluids
3. Use same motor and piping systems to circulate the fluid

3 solutions are generated using this solution step.

Next step is to determine the working principle of an existing assembly / target system. The working principle of all the assemblies is forced transport of the fluid involved in that assembly. Then the alternate assemblies that embody the same working principle of the existing assembly are found. For example, an alternate assembly that embodies the existing working principle of the air transport assembly is a variable speed fan assembly. Likewise, alternate assemblies that embody the existing working principle for the existing four assemblies that comprise the target system are tabulated in Table 5.2.

Table 5.2 Working Principle Analysis Using Existing Working Principle

Assembly	Existing Working principle	Alternate assemblies embodying the existing working principle
Air transport assembly	Forced transport (air), pressure difference	1. Variable speed fan assembly 2. Compressed air channel assembly
Engine coolant transport assembly	Forced transport (coolant)	1. Stainless steel vortex tube assembly, 2. Liquid Nitrogen Cooling (LNC) assembly
Transmission oil assembly	Forced transport (transmission oil)	- NA -
Refrigerant transport assembly	Forced transport (refrigerant)	1. Vortex cooling assembly that use compressed air 2. Plasma air purifying assembly

From the Table, it can be observed that 6 alternate assemblies are identified. Hence, this step yielded 5 solutions.

Next, an alternate working principle of an existing assembly is found. Then, alternate assemblies that embody the alternate working principle of the existing assembly are found. Later, alternate assemblies that embody the alternate working principle are found. For example, an alternate working principle that embodies the working principle for an existing engine coolant transport assembly is peltier effect. The alternate assembly that embodies the pressure difference is NEMA thermoelectric cooling assembly. Likewise, alternate assemblies for alternate working principles that embody the existing assembly are listed for the four assemblies that comprise the target system. They are tabulated in Table 5.3

Table 5.3 Working Principle Analysis Using Alternate Working Principle

Assembly	Alternate working principle	Alternate assemblies embodying the alternate working principle
Air transport assembly	NA	NA
Engine coolant transport assembly	o Gravity o Peltier effect o Temperature difference	1. Bulk powder cooling assembly 2. NEMA thermoelectric cooling assembly 3. Heat pipe assembly
Transmission oil assembly	NA	NA
Refrigerant transport assembly	o Peltier effect o Electromagnetic induction o Evaporation o Dehumidification	1. Thermoelectric cooling assembly 2. Inverter/Charger assembly 3. Evaporative cooling assembly 4. Dehumidifier

From the Table, it can be observed that 7 alternate assemblies embodying their corresponding alternate working principles are identified. Hence, this step yielded 8 solutions.

This phase (phase 4) has yielded 16 solutions cumulatively. They are:

1. Using same fluid to remove heat from engine, transmission and cabin of an automobile
2. Using same heat exchanger to remove heat from engine, transmission and cabin
3. Using same motor assembly to circulate the fluid
4. Replacing the existing air transport assembly with variable speed fan assembly
5. Replacing the existing air transport assembly with air channel assembly
6. Replacing the engine coolant assembly with Stainless steel vortex tube assembly
7. Replacing the engine coolant assembly with Liquid Nitrogen Cooling (LNC) assembly
8. Replacing the engine coolant assembly with Bulk powder cooling assembly
9. Replacing the engine coolant assembly with NEMA thermoelectric cooling assembly
10. Replacing the engine coolant assembly with heat pipe assembly
11. Replacing the refrigerant transport assembly with vortex cooling assembly that use compressed air
12. Replacing the refrigerant transport assembly with Plasma air purifying assembly
13. Replacing the refrigerant transport assembly with Thermoelectric cooling assembly
14. Replacing the refrigerant transport assembly with Inverter/Charger assembly
15. Replacing the refrigerant transport assembly with Evaporative cooling assembly
16. Replacing the refrigerant transport assembly with Dehumidifier

Phase 5: Feasibility study:

In this phase, each solution generated in the previous phase is analyzed for its feasibility by conducting a feasibility study.

1. Use same fluid to remove heat from engine, transmission and cabin of an automobile

This solution requires a new fluid that is capable of removing heat from engine, transmission and cabin. Existing fluids does not do so. Research is being carried out in the heat transfer field pertaining to this solution. Since the technology does not exist, this solution is categorized as an infeasible solution.

2. Use same heat exchanger to remove heat from engine, transmission and cabin

Implementing this solution would require extra hosing but eliminates the use of liquid-liquid heat exchanger and condenser which has the potential to save ~ 2.8 kg i.e., approximately 10% cooling system mass. Also, investigating a light weight material for the radiator can potentially reduce the mass. However, this might require a big radiator and hence more space. Since, this technology exists, it is categorized as a feasible solution.

3. Use same motor assembly to circulate the fluid

A powerpack motor assembly that consists of motor, piping systems, fasteners, weighs 2.5kg. It is built on the BMC 600 watt frame can safely run at up to 48 volts and deliver greater torque [46]. Implementing this solution requires extra belts. Considering this addition, this solution has the potential to eliminate separate motors (fan motor, coolant motor and refrigerant motor) and save ~ 7.5 kg. i.e., ~ 25% systems mass. This is categorized as a feasible solution.

4. Replacing the existing air transport assembly with a variable speed fan assembly

A sun variable speed fan assembly weighs 3.5 kg [57] and has mass considerably less than the existing fan assembly. But, the sun variable speed fan assembly does not provide enough torque required to transfer heat from coolant to the atmosphere. Hence, this solution is considered as an infeasible solution.

5. Replacing the existing air transport assembly with a compressed air channel assembly

The compressed air channel assembly does not produce the necessary torque to force the required air [47]. So, this solution is categorized as an infeasible solution.

6. Replacing the engine coolant assembly with a stainless steel vortex tube assembly

As stainless steel vortex tube assembly weighs 0.4 kg [48, 49]. This technology has been proven to work for spot cooling in machining operations and has comparatively less mass when compared to the existing engine coolant transport assembly. Incorporating a series of spot injectors at several points in the engine might lead to effective removal of heat. A series of ten spot injectors weighs 4 kg (10 * 0.4 kg) and has the potential to reduce mass of the engine coolant transport assembly considerably, i.e., approximately 25%. Therefore, it could be considered for future implementation. So, it is categorized as a feasible solution. However, this might require more air to be circulated into the engine to effectively remove the generated heat.

7. Replacing the engine coolant assembly with a Liquid Nitrogen Cooling (LNC) assembly

LNC assembly has the potential to reduce mass of the engine coolant transport assembly considerably but might not produce the required engine cooling capacity [47]. Hence, it is categorized as an infeasible solution.

8. Replacing the engine coolant assembly with a Bulk powder cooling assembly

A bulk powder cooling assembly does the desired functionality of removing heat but it is guesstimated that the assembly might weigh more than the existing solution [47]. Hence, it is categorized as an infeasible solution.

9. Replacing the engine coolant assembly with a NEMA thermoelectric cooling assembly

The NEMA thermoelectric cooling assembly does not produce the required cooling capacity that the engine coolant transport assembly does [47]. Therefore, it is categorized as an infeasible solution.

10. Replacing the engine coolant assembly with a heat pipe assembly

Since heat pipes have a much higher heat transfer rate, less liquid volume would be needed to fill the heat pipes. Feasibility depends on the ability to tune heat pipes to work under varying working fluid temperatures. A heat pipe assembly has the potential to reduce mass of the cooling system by ~10%, as the estimated mass savings of radiator, condenser, and working fluids is ~ 3000 g. [50, 58]. Therefore, it is categorized as a feasible solution.

11. Replacing the refrigerant transport assembly with a vortex cooling assembly that use compressed air

The same vortex assembly discussed in solution 6 can be investigated for potentially replacing the refrigerant transport assembly using a series of spot injectors

[48, 49]. This has the potential to reduce mass by ~5%. Therefore, it is categorized as a feasible solution.

12. Replacing the refrigerant transport assembly with a plasma air purifying assembly.

The Plasma air purifying assembly does the intended functionality but does not provide the required refrigeration capacity [47]. Therefore, it is categorized as an infeasible solution.

13. Replacing the refrigerant transport assembly with thermoelectric cooling assembly

Thermoelectric coolers can be used to remove thousands of watts heat and have been used in a wide spectrum of heat removing applications. Multiple modules could be mounted in parallel and used to increase total heat pump performance [50]. The mass of the thermoelectric cooler power assembly is 0.55 kg. Hence, six modules that produce the required cooling performance weigh 3.3kg. Therefore, this solution has the potential to save 1.2 kg i.e. ~5% of the cooling system mass. Therefore, it is categorized as a feasible solution.

14. Replacing the refrigerant transport assembly with an Inverter/Charger assembly

The Inverter/Charger assembly is a complex assembly that requires more mass than the existing assembly [47]. Therefore, it is categorized as an infeasible solution.

15. Replacing the refrigerant transport assembly with an evaporative cooling assembly

Evaporative coolers exist but require more space and mass [47]. Therefore, this solution is categorized as infeasible.

16. Replacing the refrigerant transport assembly with dehumidifier

Dehumidifier has more mass when compared to the refrigerant transport assembly [51]. Therefore, it is categorized as an infeasible solution.

The feasible solutions are listed below:

Feasible solutions (6):

1. Using the same heat exchanger to remove heat from engine, transmission and cabin
2. Using the same motor assembly to circulate the fluid
3. Replacing the engine coolant assembly with a stainless steel vortex tube assembly
4. Replacing the engine coolant assembly with heat pipe assembly
5. Replacing the refrigerant transport assembly with vortex cooling assembly that use compressed air
6. Replacing the refrigerant transport assembly with thermoelectric cooling assembly

This case study validates the hypothesis that the systematic method can be used to generate solutions at a higher level of the hierarchy thereby answering the research question 3. Also, the list of feasible solutions obtained using this method is different from those obtained using the systematic method to generate solutions at the lower level of the hierarchy. This validates the hypothesis that additional solutions can be generated using the method discussed in section 5.3, thereby answering research question 4.

CHAPTER 6

VISUALIZATION TOOL – DEVELOPMENT AND IMPLEMENTATION

6.1 Introduction

A matrix-based representation scheme allows effective change propagation, provided the entities in the column headings of one matrix become the ones in the row headings of the successive matrix. As the modeling scheme developed in this research falls into this category, interpreting the change propagation is possible. For instance, if the user/designer wishes to remove a component, then other entities related to that component in that matrix and in other matrices in the primary level should be identified and considered before eliminating the component. Doing this manually may be a difficult process and prone to human error. These aspects are taken into consideration and a tool to visualize the change propagation (accompanying the modeling scheme) is developed as a part of this research is presented.

6.2 Visualization Tool

In order to visualize the change propagation, the following steps are involved:

1. Selecting and clicking on the target entity. (a component for instance)
2. Tracking the correlation of the target entity with the entities in all the matrices at the primary level.

3. Tracing the propagation of the correlated entities with respect to the related entities in other levels (secondary to sixth level) of the model.
4. Highlighting the correlated entities in the matrix across all the levels
5. Identifying the strong, weak and nil relationships for the target entity across matrices in all the levels of the model.
6. Color coding the strong, weak and nil relationships with red, yellow and green colors respectively.
7. Listing all the correlated entities in the comment box of the target entity.

Steps 2-7 are automated in the visualization tool. Doing these steps manually is a tedious process especially when the number of entities in each domain is more. These steps are interpreted in a more user-friendly manner in the visualization tool. However, the decision making for the user's intended objective (for example, analyzing the effect of removing the thermostat over different domains in the model) is a primary requisite. This solicits the designer's knowledge about the system/sub-system under analysis.

As described in step 6, the visualization tool uses three different color schemes to highlight the correlated entities with respect to the target entity. If any entity (that is correlated to the target entity) is related to two or more entities in a matrix (implies sum across row/column is greater or equal to 2), then that entity is highlighted with a red color and represents a strong correlation. If any entity (that is correlated to the target entity) is related to only one entity in a matrix (implies sum across row/column is equal to 1), then that entity is highlighted with the yellow color and represents a weak correlation. If any entity (that is correlated to the target entity) is not related to any entity in a matrix (implies sum across row/column is equal to 0), then that entity is highlighted in green and shows no correlation with other entities. A simple arbitrary example is discussed as shown in Figure 6.1. Assuming that EE in matrix 3 is the target entity clicked by the user, the following color pattern is generated in the matrices.

Matrix1	O	P	Q	R	S	T	Sum
U	0	1	0	1	0	1	3
V	0	1	0	0	0	1	2
X	1	0	0	0	1	0	2
Y	1	1	0	1	0	1	4
Z	1	1	0	0	1	1	4
Sum	3	4	0	2	2	4	

Matrix2	I	J	K	L	Sum
O	0	1	0	0	1
P	1	0	0	0	1
Q	0	0	0	1	1
R	0	1	1	0	2
S	1	1	0	0	2
T	0	1	0	0	1
Sum	2	4	1	1	

Matrix3	AA	BB	CC	DD	EE	Sum
I	0	-1	1	0	0	2
J	1	1	0	-1	0	3
K	0	0	0	0	1	1
L	0	1	-1	0	1	3
Sum	1	3	2	1	2	

Figure 6.1 Visualization in Three Matrices

Entity EE in matrix 3 is related to K and L in that matrix. K and L are in turn related to Q and R in matrix 2. Q is not related to any entity in matrix 1, while R is related to U and Y in matrix 1. A correlation in any cell of a matrix is represented by 1 or -1. U, Y and R are highlighted in red since their sum is greater than or equal to two. In matrix 1, Q is highlighted in green since its sum is zero. In matrix 2, Q, K, L is highlighted in yellow since their sum is equal to 1 and R is highlighted in red since its sum is equal to two. K in matrix 3 is highlighted in yellow since its sum is equal to 1 while EE and L are highlighted in red since their sum is greater than or equal to two.

An underlying fact about highlighting the correlated cells with 3 different colors is the visual attention-direction capability of such an approach. In order to facilitate various reasoning skills using the visualization tool, two algorithms are developed. Flowcharts of those algorithms are shown in Figures 6.2 and 6.3.

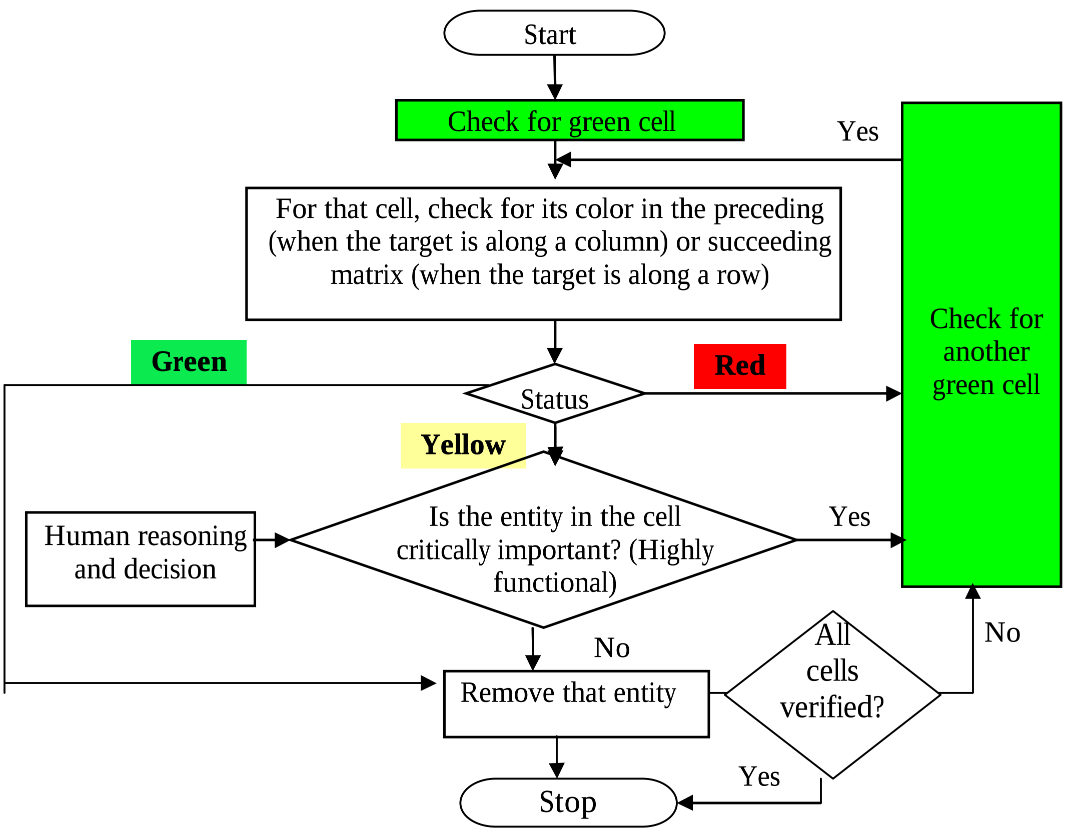


Figure 6.2 Algorithm 1: If a Cell has No Correlation (Green Color Cell)

Following the algorithm 1, Q is the only green cell in the three matrices. Green color cell Q is not related to any entity in matrix 1 but it is related only one entity in matrix 2. So, if this correlation in matrix 2 is critically low functionality, then Q can be potentially removed. But, if this correlation is critically high, then Q cannot be removed. Therefore, another entity with green color is selected and the same reasoning is implemented. If there are no further green cells, then the analysis is complete. The second algorithm is shown below.

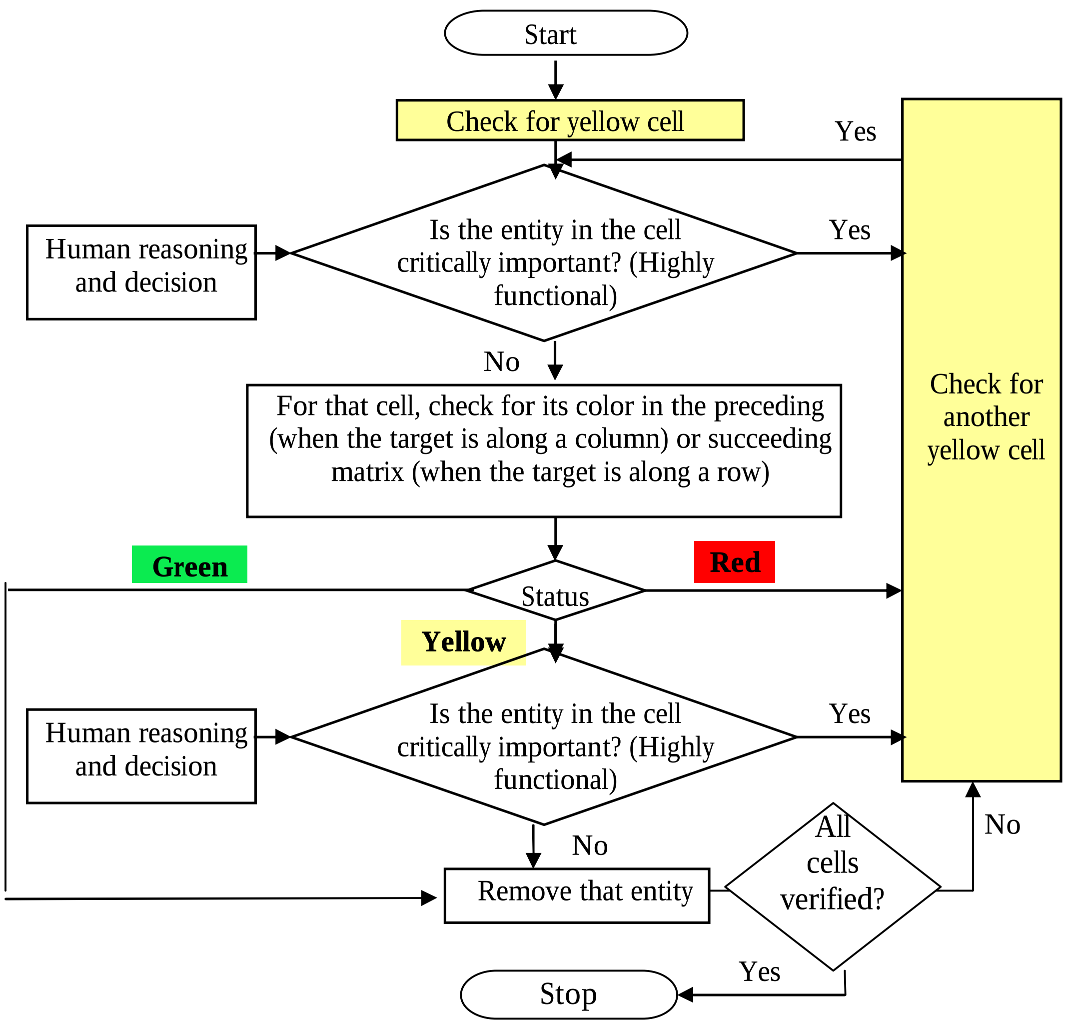


Figure 6.3 Algorithm 2: If a Cell has Only One Correlation (Yellow Color Cell)

Following the algorithm 2, K, L, Q and K are yellow cells in the three matrices. K is selected first. Yellow color cell K is related to only one entity in matrix 2. So, if this correlation in matrix 2 is critically low, then its status is checked in its succeeding matrix, i.e., matrix 3. K in matrix 3 is also related to only one entity. So, if this correlation in matrix 3 is critically low, then K can be potentially removed. But, if this correlation is critically high (in terms of functionality), then K cannot be removed. Therefore, another entity with yellow color is selected. So, L is selected next. It is related to only one entity in matrix 2. So, if this correlation in matrix 2 is critically low, then its status is checked in its succeeding matrix i.e., matrix 3. L in matrix 3 is also related to three entities and it cannot be removed. Therefore, another entity with yellow color is selected and the same reasoning is implemented. If there are no further yellow cells, then the analysis is complete.

6.3 Using Visualization Tool in the Excel Template

As discussed in the previous section, 6 out of 7 steps required to visualize the change propagation have been automated in the Excel template. The code is written in VBA embedded in Microsoft Excel. The order of matrices in the Excel file cannot be modified as the structure of the Excel file is locked. Various commands have been incorporated in the Excel template to ease the visualization process. Also, there are certain procedures to be followed in order to execute the visualization procedure trouble-free. These are discussed in detail in this section.

While entering the information in the matrices of the Excel sheet, the design mode is ON. In order to use the visualization tool and command buttons in the

Excel sheet, the design mode should be turned off. The guideline is given in Figure 6.4.

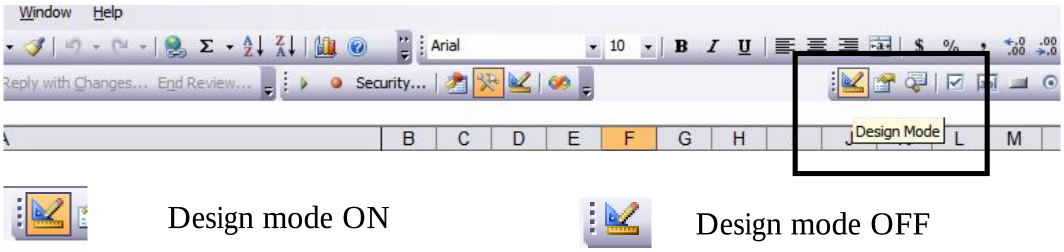


Figure 6.4 Screenshot of the Design Mode in Microsoft Excel

Failure to do so may result in unexpected behavior due to the macros embedded in the template. While turning the design mode off, there might be a high probability to get an alert as shown in the screenshot shown in Figure 6.5.

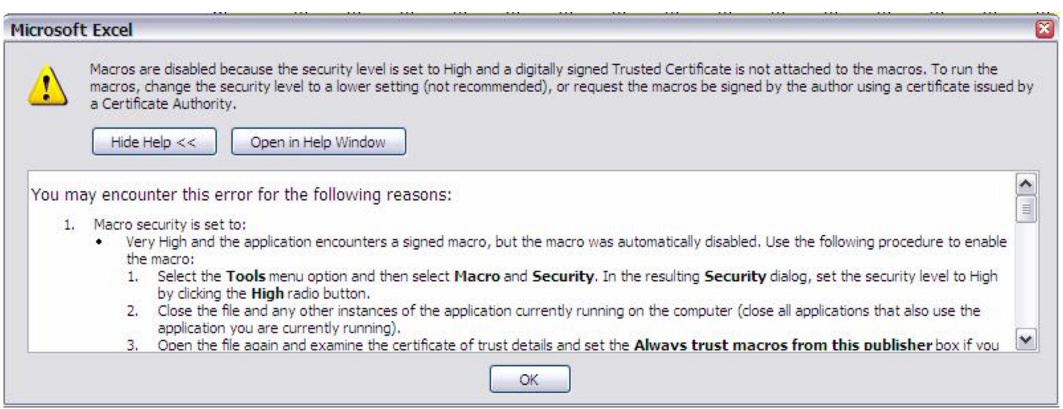
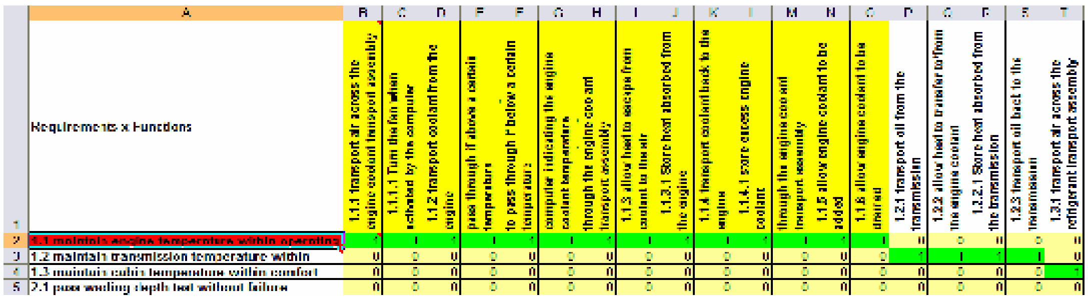


Figure 6.5 Screenshot of Macro Activation Pop-up Window

If this alert appears, click OK and then follow the steps given below:

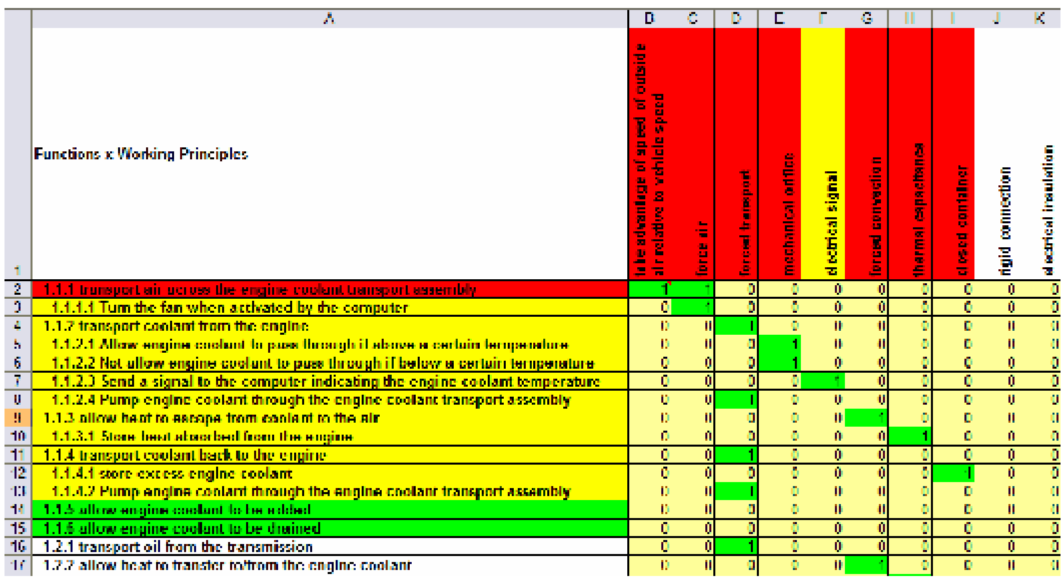
1. Click Tools->Macro->Security.
2. Click on the Medium option/radio button.
3. Save the Excel workbook.
4. Exit the application.
5. Open the Excel file again.

For the cooling system, when the requirement 1.1 is clicked by the user, then the correlated elements are displayed as shown below. Visualization in the two primary level matrices is shown in Figure 6.6 and Figure 6.7. Similarly, visualization in the rest of the matrices of the primary level and other levels (secondary to sixth) of the modeling scheme is obtained.



Requirements x Functions	1.1.1 transport air across the engine coolant transport assembly	1.1.1.1 Turn the fan when activated by the computer	1.1.2 transport coolant from the engine	pass through if above a certain temperature	to pass through if below a certain temperature	computer indicating the engine coolant temperature	through the engine coolant transport assembly	1.1.3 allow heat to escape from coolant to the air	1.1.3.1 Store heat absorbed from the engine	1.1.4 transport coolant back to the engine	1.1.4.1 store excess engine coolant	through the engine coolant transport assembly	1.1.5 allow engine coolant to be added	1.1.6 allow engine coolant to be drained	1.2.1 transport oil from the transmission	1.2.2 allow heat to transfer to/from the engine coolant	1.2.2.1 Store heat absorbed from the transmission	1.2.3 transport oil back to the transmission	1.3.1 transport air across the refrigerant transport assembly
1.1 maintain engine temperature within operating	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
1.2 maintain transmission temperature within	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0
1.3 maintain cabin temperature within comfort	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2.1 pass wading depth test without failure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6.6 Visualization in Requirements x Functions Matrix



Functions x Working Principles	take advantage of speed of outside air relative to vehicle speed	force air	forced transport	mechanical orifice	electrical signal	forced convection	thermal capacitance	closed container	rigid connection	electrical insulation
1.1.1 transport air across the engine coolant transport assembly	1	1	0	0	0	0	0	0	0	0
1.1.1.1 Turn the fan when activated by the computer	0	1	0	0	0	0	0	0	0	0
1.1.2 transport coolant from the engine	0	0	1	0	0	0	0	0	0	0
1.1.2.1 Allow engine coolant to pass through if above a certain temperature	0	0	0	1	0	0	0	0	0	0
1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	0	0	0	1	0	0	0	0	0	0
1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	0	0	0	0	1	0	0	0	0	0
1.1.2.4 Pump engine coolant through the engine coolant transport assembly	0	0	1	0	0	0	0	0	0	0
1.1.3 allow heat to escape from coolant to the air	0	0	0	0	0	1	0	0	0	0
1.1.3.1 Store heat absorbed from the engine	0	0	0	0	0	0	1	0	0	0
1.1.4 transport coolant back to the engine	0	0	1	0	0	0	0	0	0	0
1.1.4.1 store excess engine coolant	0	0	0	0	0	0	0	1	0	0
1.1.4.2 Pump engine coolant through the engine coolant transport assembly	0	0	1	0	0	0	0	0	0	0
1.1.5 allow engine coolant to be added	0	0	0	0	0	0	0	0	0	0
1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	0	0	0
1.2.1 transport oil from the transmission	0	0	1	0	0	0	0	0	0	0
1.2.2 allow heat to transfer to/from the engine coolant	0	0	0	0	0	1	0	0	0	0

Figure 6.7 Visualization in Functions x Working Principles Matrix

Also, all the entities that are correlated to the target entity are listed in its comment box. Figure 6.8 shows different entities in various primary level matrices that are related to the target entity. The entities listed in the comment box are arranged in the corresponding order of the matrices in the primary level.

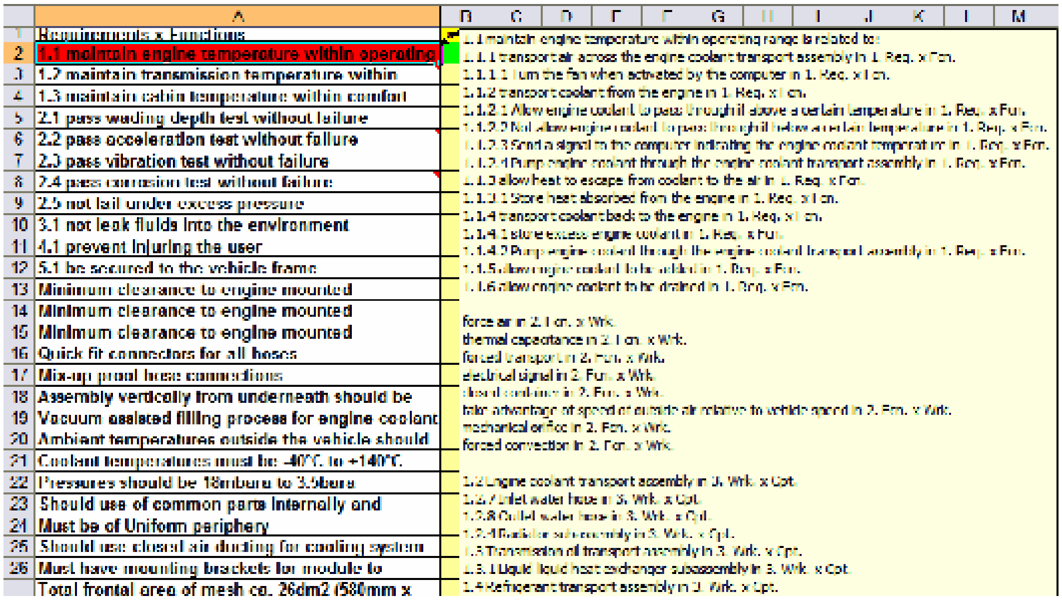


Figure 6.8 Report Generation in the Comment Box of the Target Entity

After the visualization pattern is obtained in the primary level matrices, the following command box appears as shown in Figure 6.9.

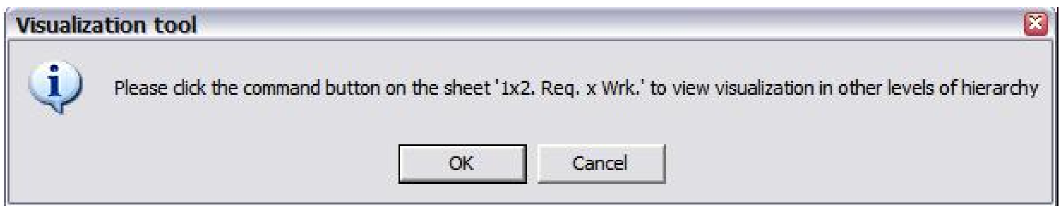
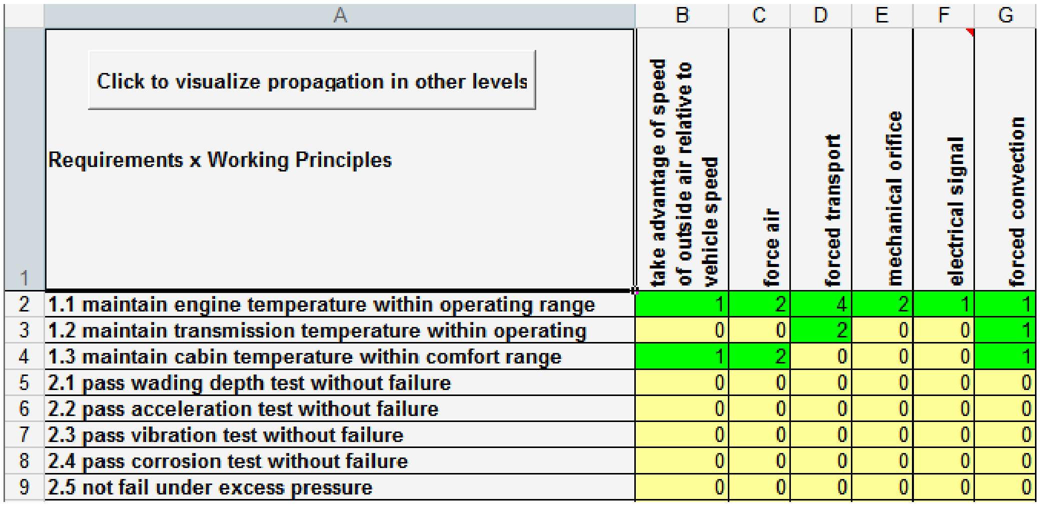


Figure 6.9 Screenshot of an Information Box Seeking User's Input

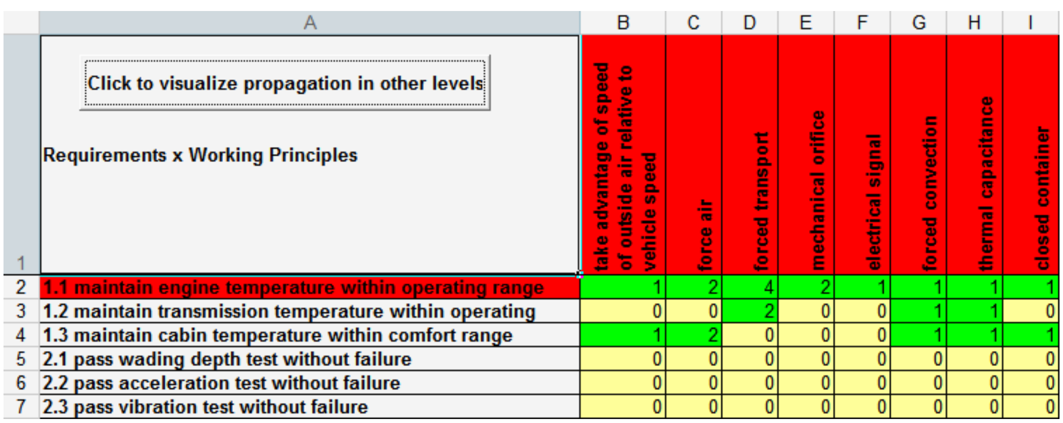
Clicking OK will activate the first matrix at the secondary level, i.e., requirements to working principles matrix. Then, click the command button in the cell A1 of this matrix as shown in Figure 6.10.



	A	B	C	D	E	F	G
1	Click to visualize propagation in other levels Requirements x Working Principles	take advantage of speed of outside air relative to vehicle speed	force air	forced transport	mechanical orifice	electrical signal	forced convection
2	1.1 maintain engine temperature within operating range	1	2	4	2	1	1
3	1.2 maintain transmission temperature within operating	0	0	2	0	0	1
4	1.3 maintain cabin temperature within comfort range	1	2	0	0	0	1
5	2.1 pass wading depth test without failure	0	0	0	0	0	0
6	2.2 pass acceleration test without failure	0	0	0	0	0	0
7	2.3 pass vibration test without failure	0	0	0	0	0	0
8	2.4 pass corrosion test without failure	0	0	0	0	0	0
9	2.5 not fail under excess pressure	0	0	0	0	0	0

Figure 6.10 Screenshot of a Secondary Level Matrix with the Command Button

Clicking the command button generates the visualization pattern in all the matrices in all the other levels of hierarchy (secondary to sixth). A sample of a secondary level matrix showing the visualization pattern is shown in Figure 6.11.

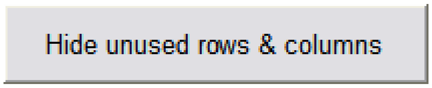


	A	B	C	D	E	F	G	H	I
1	Click to visualize propagation in other levels Requirements x Working Principles	take advantage of speed of outside air relative to vehicle speed	force air	forced transport	mechanical orifice	electrical signal	forced convection	thermal capacitance	closed container
2	1.1 maintain engine temperature within operating range	1	2	4	2	1	1	1	1
3	1.2 maintain transmission temperature within operating	0	0	2	0	0	1	1	0
4	1.3 maintain cabin temperature within comfort range	1	2	0	0	0	1	1	1
5	2.1 pass wading depth test without failure	0	0	0	0	0	0	0	0
6	2.2 pass acceleration test without failure	0	0	0	0	0	0	0	0
7	2.3 pass vibration test without failure	0	0	0	0	0	0	0	0

Figure 6.11 Screenshot of a Secondary Level Matrix with the Visualization Pattern

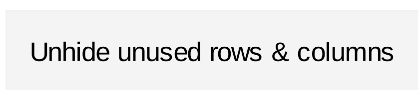
Several other macros were implemented. These are:

Hide unused rows & columns:



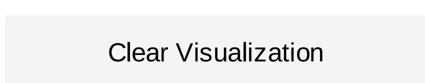
Clicking this command button hides the unused rows and columns. A row or a column that has zeros throughout that particular row or column is considered unused. For example, if rows 21 to 26 are unused, then clicking this command button hides the rows 21 to 26. The time taken to perform the operation is 5-10 seconds

Unhide unused rows & columns:



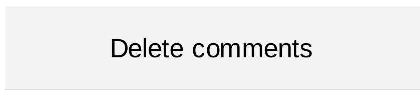
Assuming that the rows 21 to 26 were hidden by clicking the previous command button, clicking this command button unhides the hidden rows and columns. In this case, rows 21 to 26 will be unhidden. After unhiding the rows and columns, they can be used to enter any information. The time taken to perform the operation is 5-10 seconds

Clear visualization:



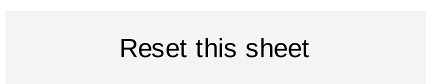
Visualization highlights the target entity and its correlated entities with different color schemes. To clear the color of these cells, this command button is used. It is not required to do this every time in order to perform the visualization. When visualization is performed for various entities, the highlighted cells are cleared and the correlated entities with respect to new target entity are highlighted automatically. So, the purpose of this command button is to reset the original color of all the cells in the Excel template according to user's convenience. The time taken to perform the operation is 2-5 seconds

Delete comments:



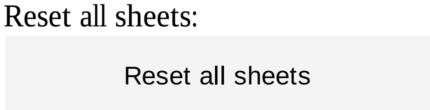
Clicking this command button deletes the comments generated in the target entity's cell during the visualization process. However, comments in cell A1 of all the matrices will not be deleted. Those comments give a brief description about each matrix. The time taken to perform the operation is 2-5 seconds

Reset this sheet:



This command button resets a particular sheet and brings it back to the original state (cells and columns with zeros). The time taken to perform the operation is 2-5 seconds

Reset all sheets:



This command button resets all sheets in the Excel file and brings it back to its original state (cells and columns with zeros). The time taken to perform the operation is 5-15 seconds

Freeze/Unfreeze panes:

Column A and Row 1 of all the matrices are freezed to view the entities even when the sheet is scrolled vertically or horizontally. To freeze/unfreeze the panes, do the following:

1. Click a cell in the worksheet
2. Click the Window tab in the menu
3. Click freeze/unfreeze panes

Unlock cells:

Matrices that are generated automatically in the secondary level to sixth level are locked to prevent user/designer from any modifying information. To unlock cells, do the following:

1. Click the sheet to be unlocked.
2. Click the Tools tab in the menu
3. Click Protection
4. Click Unprotect worksheet
5. Enter password:
    a. Password is bmwclemson
    b. Note that the password is case-sensitive. Letters in the password are all in lower case.

Handling rare execution errors:

Though the source code has been extensively tested to eliminate execution errors, they may occur occasionally. If an execution error occurs, click End. A screenshot of an execution error is shown in Figure 6.12.

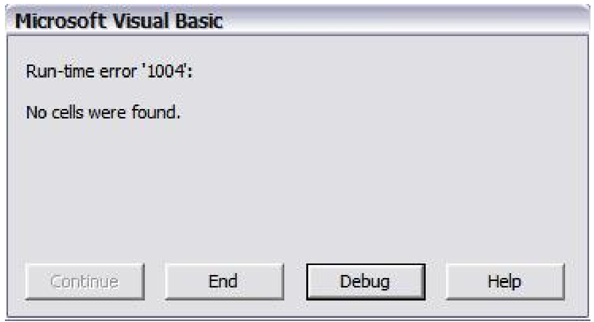


Figure 6.12 Screenshot of a Run Time Error While Using the Visualization Tool

The research questions listed in Chapter 1 have been answered in the chapters 3, 4, 5 and 6. Summary, conclusions and future work are discussed in the next chapter.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

7.1 Introduction

In this final chapter, concluding remarks are given based upon the various approaches adopted throughout this thesis to answer the research questions listed in chapter 1. Major points in each chapter are discussed thereby emphasizing the contribution made in this research in the development of an engineering design method. Finally, suggestions for future work are given.

7.2 Summary and Conclusions

7.2.1 Summary

A literature review survey was performed on the existing requirement modeling approaches, and requirements management software. It was found that no single existing modeling approach or software package provided the necessary flexibility to handle the types of requirements and operations that allow for the creation of models linking requirements, functions, components, and tests, for the propagation of change when an entity in a domain is modified/removed and for determining what effect changes in the model would have on the system mass.

In order to develop a modeling scheme, an appropriate representation scheme was required. Advantages and limitations of several representation schemes were discussed and the matrix based representation scheme was selected for the modeling scheme because of its ease of representation, capability to handle large data and ability to facilitate effective traceability between various domains in the model. Three additional domains were added to the matrix-based modeling scheme to acquire a deeper understanding of the system under analysis. They are: working principles (associated with functions), component parameters (derived from components) and test measures (derived from tests). The seven domains form the primary level matrices. The secondary to sixth level matrices are obtained by multiplying the respective primary level matrices.

A systematic method was developed to populate the primary level matrices, perform consistency checks to analyze and improve the consistency of the matrices in the secondary to sixth levels, execute steps to find potential solutions that reduce the mass of the system, and conduct a feasibility study to find the possible solution(s) and combination of feasible solutions for mass reduction that can be considered for further development. Seven solution generating steps were identified. The BMW Z4 cooling system case study was conducted to verify if the systematic method generated potential solutions for minimizing mass. The case study yielded 25 solutions out of which 9 appeared to be feasible and 16 unfeasible. As the systematic method was considered to be time intensive, a more concise method, the M^5 method, was developed. The BMW Z4 cooling system was again used for conducting a case study on the M^5 method and 63 solutions were generated. This showed that a systematic method could be used to generate solutions at the lowest level of the hierarchy for minimizing the mass of a system / sub-system under analysis.

In order to analyze the system at a higher level of the hierarchy, the information gained at the lower level was transferred to a higher level using two metrics M1 and M2 that represent the degree and structure of interaction in a matrix.

These metrics serve as attention directing parameters to make meaningful observations at a higher level of the hierarchy. A systematic method was developed to generate solutions for minimizing mass at a higher level of the hierarchy. Four solution generating steps were included in the method. Another BMW Z4 cooling system case study was conducted to validate the method. 16 solutions were generated out of which 6 were considered feasible and 10 were considered infeasible. The solutions that were generated at the higher level of the hierarchy were different to those generated at the lowest level of the hierarchy.

A visualization tool was developed to enable the user to visualize the change propagation in a systematic way. Two algorithms were developed to remove an entity that is low in criticality. Change propagation at all the levels (primary to sixth level) of the modeling scheme was incorporated in the visualization tool to enhance or facilitate the traceability of the developed model.

7.2.2 Conclusions

Systematic methods to generate solutions to reduce the mass of a complex system at various levels of its hierarchy, and a visualization tool have been developed in this research. They facilitate the creation of models linking requirements, functions, components, and tests. They allow the examination of the effects of changing any of these entities on the others and the determination of what effect changes in the model would have on the system mass, thereby establishing a systematic method to generate solutions for reducing the mass of a complex system under analysis. The novel matrix based modeling scheme and the systematic method developed in this research consider the current design, analyze the impact of the requirements on the component characteristics and identify potential areas to improve. Since the solutions that were generated for the BMW Z4 cooling system using the comprehensive method were recovered using the fast method (M^5 method) along with a handful of other potential solutions, the latter can be applied to a complex system to generate solutions for minimizing mass in lesser time. On the other hand, the comprehensive method can be used for a deeper analysis and understanding of the system under investigation. It may provide a more systematic method to build a House of Quality for the system under consideration and would be more indicative to use if the effects of changing components has to be studied thoroughly. Furthermore, the comprehensive method allows the user to visualize the change propagation since the visualization tool has been incorporated in the comprehensive method but not in the fast method. The case study conducted using the M^5 method yielded more solutions than the comprehensive method because of the additional solution strategies available in the former. The M^5 method has 11 solution strategies while the comprehensive method has 7. For example, “Identify solutions by considering low-criticality components that could be removed or combined” is an additional solution strategy found in the M^5 method. Both the comprehensive and fast methods are attention gathering approaches in the same lines of QFD. They may also be used to coordinate with suppliers for potential improvement in mass reduction of a complex system. The method developed to generate solutions at a higher level of the hierarchy enables the users to have the freedom to analyze the system at any level in a hierarchy and not be restricted only to a component level analysis. Irrespective of the size of the matrices, the importance of the metrics M1 and M2 is that, they can be used to transfer the information gained at a lower level of the hierarchy to a level above to represent the degree and structure of interaction in the matrices and compare them. However, the metrics do not represent the individual correlations obtained between the entities at the lower level. The metrics can be used to transfer the information obtained at the lower level of the hierarchy to a level above but not the vice versa. The visualization tool is a user friendly tool to analyze the what-if scenarios and interpret the change propagation of an entity across various domains in the modeling scheme. The users can interpret the degree of the correlations (nil, weak, medium / strong) with different colors using the excel template that accompanies the modeling scheme. However, this tool does not calculate the change in mass and cost when the alternative solutions are considered.

The limitation of the methods developed in this research is that the quality of the solutions depends upon the user's knowledge and skills, irrespective of the methods' robust solution generating strategies. This implies that, with increased experience or applying this method in a group setting, results in increased quality and completeness of the solutions that are generated. The method developed has been validated only on several automotive systems, namely, the cooling system, seat and the accelerator pedal module. These were used to help develop the approach and are included in the electronic appendix. The method has not been used to analyze the impact of instantiating the proposed solutions back into the modeling scheme. The systematic method lacks the ability to automatically calculate the mass and cost while considering the alternative solutions. Finally, though the method identifies potential areas to improve in terms of mass reduction, it does not incorporate a benchmarking strategy, such as the one found in HoQ.

7.3 Future Work

The systematic method for generating solutions was developed in a research setting and should be implemented in an industrial setting. Inputs from experts that have professional experience in designing specific systems could help in further refining the method. Case studies can be conducted on other systems to verify the robustness of the method.

The House of Quality maps the customer requirements to engineering characteristics and does not consider the impact of other important domains like functions, components and tests. As the modeling scheme considers all the important domains that govern the system, as suggested earlier, it would be interesting to analyze if the modeling scheme could lead to an improved approach to constructing the HoQ. Also, along the lines of HoQ, the modeling scheme and method could be adapted and used for competitive benchmarking to compare the system under analysis with those of the competitors, thereby serving as a benchmarking tool.

The systematic method can be applied to different implementations of the same systems with different architectures and mass, and the requirements propagation can be analyzed. For example, the systematic method applied to the BMW Z4 cooling system in this research, can be used to analyze the Lexus SC 07 cooling system or the Chevrolet Corvette cooling system. The functionality of the cooling system in all these cases remain the same at the top level of the hierarchy, but the architecture and mass of the cooling systems of all three implementations may differ. This implies that the requirements (functional or non-functional ones) imposed on these architectures may be different. Various research questions that can be answered by considering this aspect of future work are:

- o Does a different amount of heat rejection in different systems lead to different solutions or are the solutions simply scaled?
- o If the amount of heat rejection is the same, have the same solutions been implemented?
- o Are they different functional requirements or are the solutions dependent on other characteristics?

Thus, the propagation of different sets of requirements in order to perform the same functionality could be an interesting research topic for future work.

The systematic method generates solutions for minimizing mass but does not deal with infusing the feasible solutions back into the modeling scheme and analyzing the corresponding change on the existing requirements, functions, working principles, test measures and tests. Doing this would enable one to analyze the change brought by imposing the solution back into the modeling scheme, i.e., modifying the existing requirements according to the new solution, or removing / adding functionalities or tests that satisfy the new solution. Likewise, the impact of change in mass and cost while considering the proposed solutions for future development can be studied. This can be shown as a running total in the modeling scheme thereby enabling the user to immediately analyze the effects of the new solution on mass and cost. Also, this aspect can be automated in the Excel template in order to reduce the human effort and eliminate human error. Cut-off limits can be assigned for both mass and cost. If the running total is above the assigned cut-off limit, various color schemes can be used to represent the change thereby enabling the user to easily understand the magnitude of change.

Overall, the modeling scheme and the systematic method developed in this research provide a firm foundation for much potential future work. Modeling requirements propagation to generate solutions for reducing the mass of a complex system could be considered as an important contribution to the fields of requirements engineering and engineering design.

APPENDICES

Appendix – A

Glossaries

Term # 1: Allocation

Definition: In the context of requirements engineering, allocation refers to the capability of the model to capture which requirements each component helps satisfy, i.e., the allocation of requirements to components.

Example: The fuel efficiency requirement is allocated to the vehicle body, the engine, the transmission, and the accelerator pedal module.

Notes: Allocation, like traceability, is vertical in the model.

Source: Fu et al [11]

Term # 2: Application Protocol 233

Acronym: AP 233

Definition: "AP233 is STEP (ISO 10303) based data exchange standard supporting the needs of the systems engineering community, consistent with emerging standards in CAD, structural, electrical, engineering analysis and support domains."

Source: AP 233 FAQ

http://csz.com/synchrosoft/AP233/FAQ/FAQ_AP233.html

Term # 3: Assembly

Definition: "The putting together of manufactured parts to make a completed product, such as a machine or electronic circuit; a set of parts so assembled."

Example: The accelerator pedal module is an assembly comprised of the pedal, housing, potentiometer, springs, and other components.

Notes: Assemblies are composed of components.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. - http://www.thefreedictionary.com/Assembly

Term # 4: Black Box

Definition: "For all functional modeling methods, a basic construct…called "black" because its internal form is deemed unknown. One can think of the product as doing something – the function – by taking in inputs, changing or modifying these inputs, and thereby creating outputs. One can represent this diagrammatically as a simple function statement with a box drawn around it."

Example:

Electrical energy → Motor → Rotational kinetic energy

Notes: A white box shows its contents (how the function is performed); a black box does not. A black box function model is usually used at the highest level of abstraction.

Source: Otto, K. and K. Wood (2001). <u>Product Design: Techniques in Reverse Engineering and New Product Development</u>. Upper Saddle River, NJ, Prentice Hall. Page 152.

Term # 5: Component

Abbreviation.: Cpt.

Definition: "A part of a mechanical or electrical complex."

Example: The potentiometer is a component of the accelerator pedal module.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. - http://www.thefreedictionary.com/Component

Term # 6: Consistency

Definition: "Agreement or logical coherence among things or parts."

Example: That the Req. / Tests matrix formulated manually yields the same (or similar) results as the Req. / Tests matrix formulated by multiplying through the primary matrices is a check on the model consistency.

Notes: Sometimes consistency is considered part of model verification or validation. However, we have reserved the term verification for checking if the requirements are met by the artifact, regardless of the model, and the term validation for checking if the model's predictions (i.e., for reducing mass) are accurate. Model consistency should be checked before model validation. Requirements verification is accomplished by running the actual tests.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. - http://www.thefreedictionary.com/Consistency

Term # 7: Criterion / Criteria

Definition: "A standard, rule, or test on which a judgment or decision can be based."

Examples: 'The coefficient of drag (the performance evaluation metric) must be 0.30 or less (the target value)' is a constraint.

‘coefficient of drag (a performance evaluation metric only)’ is a criterion.

Notes: Criteria are used to select concepts that already satisfy the constraints.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. - http://www.thefreedictionary.com/Criteria

Term # 8: Constraint

Definition: “a performance evaluation metric and target value pair that is used to constrain the final solution to exhibit additional properties belonging to the set of design configurations”

“external factors that, in some way, limit the selection of system or sybsystem characteristics. They are not directly related to the function (or functional objectrive) of the system, but apply across the set of functions for the system. They are generally imposed by factors outside the designer’s control. Cost and schedule are constraints. Size, weight, materials properties, and safety issues such as nontoxic, nonflammable materials are constraints.”

Examples: ‘The coefficient of drag (the performance evaluation metric) must be 0.30 or less (the target value)’ is a constraint.

‘coefficient of drag (a performance evaluation metric only)’ is a criterion.

‘The coefficient of drag must be minimized’ is an objective.

Constraints and objectives are both types of requirements.

Notes: The term constraint is typically used in the context of optimization: the optimal solution satisfies the constraints while minimizing some cost function. In the sense that a constraint is required to be met, constraints can be considered requirements (but not functional requirements), and vice versa. Any solution that meets the constraints is considered acceptable, but not necessarily optimal. However, a requirement could also be an objective, i.e., that some penalty function is minimized, which would not be a constraint. Several such requirements could be stated, in addition to multiple constraints, making the problem multi-objective.

Source: Otto, K. and K. Wood (2001). Product Design: Techniques in Reverse Engineering and New Product Development. Upper Saddle River, NJ, Prentice Hall. Page 802, 285.

Term # 9: Dynamic Object-Oriented Requirements System

Acronym: DOORS

Definition: "A tool from Quality Systems & Software Ltd. for handling all kinds of requirements (in fact, any information at all) as modules containing trees of text objects, qualified by an arbitrary number of user-defined attributes, and cross-linked by directional links."

Source: The Free Dictionary of On-line Computing

http://www.thefreedictionary.com/Dynamic_Object-oriented_Requirements_System

Term # 10: Function

Abbreviation : Fcn.

Definition: "a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form"

Example: The function of a motor is to convert electricity to rotary motion.

Notes: Functions describe the intended (desired) performance of the system; behaviors describe the actual performance of the system.

Source: Otto, K. and K. Wood (2001). Product Design: Techniques in Reverse Engineering and New Product Development. Upper Saddle River, NJ, Prentice Hall. Page 151.

Term # 11: Functional requirement

Abbreviation: Fcn. req.

Definition: "statements of the specific performance of a design, that is, what the device should do [or NOT do]. Functional requirements should be stated, initially, in the broadest (most generic) terms. They should focus on performance, be stated in terms of logical relationships, and be stated, initially, in 'solution neutral' terms."

Example: 'The accelerator pedal module must convert foot force to an electrical signal' is a functional requirement.

Notes: Non-functional requirements are constraints.

Source: Otto, K. and K. Wood (2001). Product Design: Techniques in Reverse Engineering and New Product Development. Upper Saddle River, NJ, Prentice Hall. Page 285.

Term # 12: Geometry

Definition: "The mathematics of the properties, measurement, and relationships of points, lines, angles, surfaces, and solids."

Example: The geometry of a shaft is a solid right cylinder with specific length and radius.

Notes: We use the term geometry to describe the physical form of components.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/geometry

Term # 13: Hierarchy

Definition: "A structure that has a predetermined ordering from high to low."

Example: "all files and folders on the hard disk are organized in a hierarchy"

Notes: A hierarchy, like a taxonomy, is organized into various levels. However, a hierarchy implies some control of lower levels from higher levels, whereas a taxonomy is purely descriptive.

Source: Computer Desktop Encyclopedia ©1981-2005 by The Computer Language Company Inc. - http://computing-dictionary.thefreedictionary.com/hierarchy

Term # 14: Interface

Definition: "A surface forming a common boundary between adjacent regions, bodies, substances, or phases."

Example: The accelerator pedal module has a male plug interface to a wiring harness.

Notes: We are using the term interface to describe physical interfaces between sub-systems, assemblies, or components.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/interface

Term # 15: Lastenheft

Definition: “product concept catalogue, specification book”

Example: Document number “10001045 - 000 - 01” is the Lastenheft for the accelerator pedal module.

Notes: An internal document from BMW listing the specifications, i.e., requirements, for an individual component.

Source: Online Dictionary German-English (ODGE)

http://odge.info/german-english/Lastenheft+%7Bn%7D.html

Term # 16: Method

Abbreviation.: Mtd.

Definition: In the context of engineering design, a method is a systematic procedure for obtaining a desired result.

Example: Failure Modes and Effects Analysis is a method for identifying and reducing failures of engineered artifacts.

Notes: Methods should not be confused with the study of methods, i.e., methodology

Source: http://wordnet.princeton.edu/perl/webwn?s=method

Term # 17: Methodology

Definition: The way in which information is found or something is done. The methodology includes the methods, procedures, and techniques used to collect and analyze information.

Example: Design methodology is the study of methods used for design.

Notes: Methodology is often confused with individual methods. Methodology is a science; methods are the subject that is studied.

Source: http://www.epa.gov/evaluate/glossary/m-esd.htm

Term # 18: Model

Definition: "A schematic description of a system, theory, or phenomenon that accounts for its known or inferred properties and may be used for further study of its characteristics."

Example: Our matrix based model allows us to study a vehicle system in terms of its requirements, functions, components, and tests.

Notes: A paradigm is a model of thinking about a subject.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/model

Term # 19: Objective

Definition: "Something worked toward or striven for; a goal."

Example: The single objective considered in our project is to minimize mass.

Notes: Constraints and objectives are both types of requirements.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/objective

Term # 20: Parameter

Abbreviation.: Param.

Definition: "One of a set of measurable factors, such as temperature and pressure, that define a system and determine its behavior and are varied in an experiment."

Example: Density, ultimate tensile strength, and thermal conductivity are all material parameters.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/parameter

Term # 21: Requirement

Abbreviationiation: Req.

Definition: "…defines what the potential users want the system to do. In modern methods these requirements should be testable, and will usually be traceable in later development stages."

Example: The vehicle must accelerate from 0 to 100 kph in 6 seconds or less is a requirement.

Notes: Requirements vary by source (industry standard, government regulation, consumer preferences, etc.). Requirements are typically stated in terms of an acceptable value or range. A test may be associated with the requirement to verify that the final artifact meets the requirement.

Source: Free Online Dictionary of Computing - http://computing-dictionary.thefreedictionary.com/requirement

Term # 22: Requirements Engineering

Abbreviation.: Req. eng.

Definition: "The task of capturing, structuring, and accurately representing the user's requirements so that they can be correctly embodied in systems which meet those requirements (i.e. are of good quality)."

Example: DOORS, SysML, SLATE, and AP233 are all requirements engineering software packages.

Notes: Requirements Engineering is more widely practiced in software engineering than in mechanical engineering.

Source: Free Online Dictionary of Computing - http://computing-dictionary.thefreedictionary.com/requirements+engineering

Term # 23: Sub-system

Definition: "A unit or device that is part of a larger system."

Example: "a disk sub-system is a part of a computer system"

Notes: The accelerator pedal module is a system in the sense that its components are functionally related and interacting. It is a sub-system in the sense that it is part of the larger vehicle system.

Source: Computer Desktop Encyclopedia copyright ©1981-2005 by The Computer Language Company Inc. - http://computing-dictionary.thefreedictionary.com/subsystem

Term # 24: System

Definition: "A group of interacting, interrelated, or interdependent elements forming a complex whole; a functionally related group of elements"

Example: The accelerator pedal module is a system.

Notes: The accelerator pedal module is also an assembly, as well as a module. It is a system in the sense that its components are functionally related and interacting. It is an assembly in the sense that its components are all physically attached. It is a module in the sense that it has clear interfaces with the rest of the vehicle.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/system

Term # 25: Taxonomy

Definition: "Division into ordered groups or categories"

Example: Maier and Fadel's taxonomy of product families includes single, parallel, evolving, and mutating product families.

Notes: Taxonomies are subjective schemes, and as such are not unique. Taxonomies should be orthogonal (divisions should not overlap) and complete (classify everything in the domain). Taxonomies vary by depth (number of levels).

Source: The American Heritage® Dictionary of the English Language, Fourth Edition © 2000 Houghton Mifflin. http://www.thefreedictionary.com/taxonomy

Term # 26: Test

Definition: "A procedure for critical evaluation; a means of determining the presence, quality, or truth of something; a trial"

Example: A wind tunnel test can be used to measure coefficient of drag of a vehicle body.

Notes: Tests are used to verify that requirements are met.

Source: The American Heritage® Dictionary of the English Language, Fourth Edition copyright ©2000 by Houghton Mifflin Company. Updated in 2003. - http://www.thefreedictionary.com/test

Term # 27: Validation

Definition: In the context of modeling, validation is the subjective procedure for checking a model's predictive results against reality, i.e., validating the model by showing that it accurately predicts real observed outcomes of the system that is modeled.

Example: A finite element model may be validated by measuring observed strains.

Notes: Models are validated by testing predictions of the models against observed behaviors; requirements are verified by testing the performance of the final artifact.

How accurate a model's predictions must be for the model to be valid is a subjective evaluation.

Source: Hazelrigg, G.A. (2003) "Thoughts on Model Validation for Engineering Design." DETC2003/DTM-48632

APPENDIX – B

Cooling System Matrices

Requirements x Functions	1.1.1 transport air across the engine coolant transport assembly	1.1.1.1 Turn the fan when activated by the computer	1.1.2 transport coolant from the engine	1.1.2.1 Allow engine coolant to pass through if above a certain temperature	1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	1.1.2.4 Pump engine coolant through the engine coolant transport assembly	1.1.3 allow heat to escape from coolant to the air	1.1.3.1 Store heat absorbed from the engine	1.1.4 transport coolant back to the engine	1.1.4.1 store excess engine coolant	1.1.4.2 Pump engine coolant through the engine coolant transport assembly	1.1.5 allow engine coolant to be added	1.1.6 allow engine coolant to be drained	1.2.1 transport oil from the transmission	1.2.2 allow heat to transfer to/from the engine coolant	1.2.2.1 Store heat absorbed from the transmission	1.2.3 transport oil back to the transmission	1.3.1 transport air across the refrigerant transport assembly	1.3.1.1 Turn the fan when activated by the computer	1.3.2 allow heat to escape from refrigerant to the air	1.3.2.1 Store water trapped in the refrigerant transport assembly	1.3.2.2 Store heat absorbed from the cabin	2.1.1 Carry ### forces exerted by water	2.1.2 Not short electronics from water	2.2.1 Carry ### forces from x direction acceleration	2.2.2 Carry ### forces from y direction acceleration	2.2.3 Carry ### forces from z direction acceleration	2.3.1 Carry ### forces from other vibrating components	2.3.2 Balance the fan to prevent vibrations	2.4.1 Do not corrode in the presence of water, salt, etc.	2.5.1 Carry ### forces from pressurizing system	3.1.1 Do not leak fluids into the nevironment	4.1.1 Prevent cutting the user	4.1.2 Prevent burning the user	5.1.1 Transmit forces to the vehicle frame	Sum	%
1.1 maintain engine temperature within operating	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	39%
1.2 maintain transmission temperature within	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	11%
1.3 maintain cabin temperature within comfort range	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5	14%
2.1 pass wading depth test without failure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	2	6%
2.2 pass acceleration test without failure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	3	8%
2.3 pass vibration test without failure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2	6%
2.4 pass corrosion test without failure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	3%
2.5 not fail under excess pressure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	3%
3.1 not leak fluids into the environment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	3%
4.1 prevent injuring the user	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	6%
5.1 be secured to the vehicle frame	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3%
Minimum clearance to engine mounted components	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted components	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted components	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick fit connectors for all hoses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mix-up proof hose connections	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Assembly vertically from underneath should be with	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Vacuum assisted filling process for engine coolant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Ambient temperatures outside the vehicle should be	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Coolant temperatures must be -40°C to +140°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures should be 18mbara to 3.5bara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use of common parts internally and	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must be of Uniform periphery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use closed air ducting for cooling system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must have mounting brackets for module to include	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh ca. 26dm2 (580mm x 449mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mesh depth max. 30mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Optional low temperature radiator for automatic transmission ca. 4.7dm2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak rate 150 l/min at 300mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
In- and outlet should be with a nominal width (NW) 32mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Bleeding outlet (integrated in inlet connector) should be NW 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Overflow outlet should be NW 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Dimensions of oil cooler's block size X=45mm; Y=165mm; Z=80mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick connectors for transmission fluid and engine coolant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Operating pressures transmission fluid should be in the range of 8bara at –40°C to +160°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures engine coolant should be in the range of 3bara at –40°C to +143°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for transmission fluid is minimum 20barg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for engine coolant is minimum 2,5barg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh of condenser should be 22.2dm2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	36	100%
%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	100%	

Figure B.1 Requirements to Functions Matrix – Primary Level Matrix

Functions x Working Principles	outside air relative to vehicle speed	force air	forced transport	mechanical orifice	electrical signal	forced convection	thermal capacitance	closed container	rigid connection	electrical insulation	counterbalance	non-corroding materials	shield corroding materials	tight connections	impervious to punctures	round edges	sheild sharp edges	keep surfaces cool	shield hot surfaces	Sum	%
1.1.1 transport air across the engine coolant transport assembly	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5%
1.1.1.1 Turn the fan when activated by the computer	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.2 transport coolant from the engine	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.2.1 Allow engine coolant to pass through if above a certain temperature	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.2.4 Pump engine coolant through the engine coolant transport assembly	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.3 allow heat to escape from coolant to the air	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.3.1 Store heat absorbed from the engine	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.4 transport coolant back to the engine	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.4.1 store excess engine coolant	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.4.2 Pump engine coolant through the engine coolant transport assembly	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.1.5 allow engine coolant to be added	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
1.2.1 transport oil from the transmission	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.2.2 allow heat to transfer to/from the engine coolant	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.2.2.1 Store heat absorbed from the transmission	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.2.3 transport oil back to the transmission	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.3.1 transport air across the refrigerant transport assembly	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5%
1.3.1.1 Turn the fan when activated by the computer	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.3.2 allow heat to escape from refrigerant to the air	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.3.2.1 Store water trapped in the refrigerant transport assembly	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	3%
1.3.2.2 Store heat absorbed from the cabin	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	3%
2.1.1 Carry ### forces exerted by water	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
2.1.2 Not short electronics from water	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	3%
2.2.1 Carry ### forces from x direction acceleration	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
2.2.2 Carry ### forces from y direction acceleration	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
2.2.3 Carry ### forces from z direction acceleration	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
2.3.1 Carry ### forces from other vibrating components	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
2.3.2 Balance the fan to prevent vibrations	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	3%
2.4.1 Do not corrode in the presence of water, salt, etc.	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2	5%
2.5.1 Carry ### forces from pressurizing system	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
3.1.1 Do not leak fluids into the neviroment	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2	5%
4.1.1 Prevent cutting the user	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	2	5%
4.1.2 Prevent burning the user	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	5%
5.1.1 Transmit forces to the vehicle frame	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
Sum	2	4	6	2	1	3	3	2	7	1	1	1	1	1	1	1	1	1	1	40	100%
%	5%	10%	15%	5%	3%	8%	8%	5%	18%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	100%	

Figure B.2 Functions to Component Matrix – Primary Level Matrix

Working Principles x Components	1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap	1.2.4 Radiator subassembly	1.2.5 Left bracket	1.2.6 Right bracket	1.2.7 Inlet water hose	1.2.8 Outlet water hose	1.2.9 Temperature sensor	1.2.10 Water pump subassembly	1.2.11 Engine coolant	1.3 Transmission oil transport assembly	heat exchanger subassembly	1.3.2 Transmission oil	1.4 Refrigerant transport assembly	1.4.1 Drying container	1.4.2 Condenser subassembly	1.4.3 Refrigerant	Sum	%
take advantage of speed of outside air relative to vehicle speed	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	2%
force air	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**5**	4%
forced transport	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	**5**	4%
mechanical orifice	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	2%
electrical signal	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**3**	2%
forced convection	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	**7**	5%
thermal capacitance	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	1	**7**	5%
closed container	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	**6**	5%
rigid connection	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	**9**	7%
electrical insulation	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**5**	4%
counterbalance	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	2%
non-corroding materials	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	0	**22**	17%
shield corroding materials	1	1	1	0	0	0	1	1	0	1	1	0	0	0	0	1	1	0	0	0	0	1	0	1	0	**11**	9%
tight connections	1	0	0	0	0	0	1	1	1	1	1	0	0	1	1	1	1	0	1	1	0	1	1	0	0	**14**	11%
impervious to punctures	1	0	0	0	0	0	1	1	1	1	1	0	0	1	1	0	1	0	1	1	0	1	1	0	0	**13**	10%
round edges	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	**4**	3%
sheild sharp edges	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	2%
keep surfaces cool	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**	2%
shield hot surfaces	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	2%
Sum	**19**	**7**	**4**	**3**	**2**	**5**	**13**	**5**	**4**	**5**	**7**	**2**	**2**	**4**	**4**	**4**	**6**	**1**	**6**	**5**	**1**	**9**	**5**	**4**	**1**	**128**	100%
%	15%	5%	3%	2%	2%	4%	10%	4%	3%	4%	5%	2%	2%	3%	3%	3%	5%	1%	5%	4%	1%	7%	4%	3%	1%	100%	
Mass	0	4701	3500	700	1	500	16726	83	884	40	5000	249	249	300	300	20	4680	4921	1598	598	1000	4500	300	2200	2000	27525	
% Mass	0%	17%	13%	3%	0%	2%	61%	0%	3%	0%	18%	1%	1%	1%	1%	0%	17%	18%	6%	2%	4%	16%	1%	8%	7%	100%	
Sum * % Mass	0.0	1.2	0.5	0.1	0.0	0.1	7.9	0.0	0.1	0.0	1.3	0.0	0.0	0.0	0.0	0.0	1.0	0.2	0.3	0.1	0.0	1.5	0.1	0.3	0.1	128.0	
% Sum * % Mass	0%	1%	0%	0%	0%	0%	6%	0%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	100%	

Figure B.3 Working Principle to Components Matrix – Primary Level Matrix

Components x Component Parameters	Max thermal power dissipation	Max electrical power draw	Solid volume	Liquid volume	Average density	Max air flow produced	Max torque delivered	Depth	Diameter	Number of blades	Blade thickness
1. Cooling system	1	1	1	1	1	0	0	0	0	0	0
1.1 Air transport assembly	0	1	1	0	1	1	0	0	0	0	0
1.1.1 Motor subassembly	0	1	0	0	1	0	1	1	1	0	0
1.1.2 Fan	0	0	0	0	1	0	0	1	1	1	1
1.1.3 Counterweight	0	0	1	0	1	0	0	0	0	0	0
1.1.4 Fan shroud	0	0	0	0	1	0	0	1	1	0	0
1.2 Engine coolant transport assembly	1	1	1	1	1	0	0	0	0	0	0
1.2.1 Thermostat	0	0	1	0	1	0	0	0	0	0	0
1.2.2 Expansion tank subassembly	0	0	1	1	1	0	0	0	0	0	0
1.2.3 Radiator cap	0	0	1	0	1	0	0	0	0	0	0
1.2.4 Radiator subassembly	0	0	1	1	1	0	0	1	0	0	0
1.2.5 Left bracket	0	0	1	0	1	0	0	0	0	0	0
1.2.6 Right bracket	0	0	1	0	1	0	0	0	0	0	0
1.2.7 Inlet water hose	0	0	0	0	1	0	0	0	0	0	0
1.2.8 Outlet water hose	0	0	0	0	1	0	0	0	0	0	0
1.2.9 Temperature sensor	0	0	1	0	1	0	0	0	0	0	0
1.2.10 Water pump subassembly	0	1	0	0	1	0	0	1	1	0	0
1.2.11 Engine coolant	0	0	0	0	0	0	0	0	0	0	0
1.3 Transmission oil transport assembl	1	1	1	1	1	0	0	0	0	0	0
1.3.1 Liquid-liquid heat exchanger suba	0	0	1	1	1	0	0	0	0	0	0
1.3.2 Transmission oil	0	0	0	0	0	0	0	0	0	0	0
1.4 Refrigerant transport assembly	1	0	1	1	1	0	0	0	0	0	0
1.4.1 Drying container	0	0	1	1	1	0	0	0	0	0	0
1.4.2 Condenser subassembly	0	0	1	1	1	0	0	1	0	0	0
1.4.3 Refrigerant	0	0	0	0	0	0	0	0	0	0	0
Sum	4	6	16	9	22	1	1	6	4	1	1
%	4%	7%	17%	10%	24%	1%	1%	7%	4%	1%	1%

Components x Component Parameters	Opening temperature	Front area	Cooling fin area	Thickness	Interior diameter	Length	Max flow rate delivered	Thermal capacitance as liquid	Density as liquid	Thermal capacitance as vapor	Density as vapor	Sum	%	Mass	% Mass	Sum * % Mass	% Sum * % Mass
1. Cooling system	0	0	0	0	0	0	0	0	0	0	0	5	5%	0	0%	0.0	0%
1.1 Air transport assembly	0	0	0	0	0	0	0	0	0	0	0	4	4%	4701	17%	0.7	1%
1.1.1 Motor subassembly	0	0	0	0	0	0	0	0	0	0	0	5	5%	3500	13%	0.6	1%
1.1.2 Fan	0	0	0	0	0	0	0	0	0	0	0	5	5%	700	3%	0.1	0%
1.1.3 Counterweight	0	0	0	0	0	0	0	0	0	0	0	2	2%	1	0%	0.0	0%
1.1.4 Fan shroud	0	0	0	0	0	0	0	0	0	0	0	3	3%	500	2%	0.1	0%
1.2 Engine coolant transport assembly	0	0	0	0	0	0	0	0	0	0	0	5	5%	16726	61%	3.0	3%
1.2.1 Thermostat	1	0	0	0	0	0	0	0	0	0	0	3	3%	83	0%	0.0	0%
1.2.2 Expansion tank subassembly	0	0	0	1	0	0	0	0	0	0	0	4	4%	884	3%	0.1	0%
1.2.3 Radiator cap	0	0	0	0	0	0	0	0	0	0	0	2	2%	40	0%	0.0	0%
1.2.4 Radiator subassembly	0	1	1	0	0	0	0	0	0	0	0	6	7%	5000	18%	1.1	1%
1.2.5 Left bracket	0	0	0	0	0	0	0	0	0	0	0	2	2%	249	1%	0.0	0%
1.2.6 Right bracket	0	0	0	0	0	0	0	0	0	0	0	2	2%	249	1%	0.0	0%
1.2.7 Inlet water hose	0	0	0	1	1	1	0	0	0	0	0	4	4%	300	1%	0.0	0%
1.2.8 Outlet water hose	0	0	0	1	1	1	0	0	0	0	0	4	4%	300	1%	0.0	0%
1.2.9 Temperature sensor	0	0	0	0	0	0	0	0	0	0	0	2	2%	20	0%	0.0	0%
1.2.10 Water pump subassembly	0	0	0	0	0	0	1	0	0	0	0	5	5%	4680	17%	0.9	1%
1.2.11 Engine coolant	0	0	0	0	0	0	0	1	1	0	0	2	2%	4921	18%	0.4	0%
1.3 Transmission oil transport assembl	0	0	0	0	0	0	0	0	0	0	0	5	5%	1598	6%	0.3	0%
1.3.1 Liquid-liquid heat exchanger suba	0	0	0	0	0	0	0	0	0	0	0	3	3%	598	2%	0.1	0%
1.3.2 Transmission oil	0	0	0	0	0	0	0	1	1	0	0	2	2%	1000	4%	0.1	0%
1.4 Refrigerant transport assembly	0	0	0	0	0	0	0	0	0	0	0	4	4%	4500	16%	0.7	1%
1.4.1 Drying container	0	0	0	0	0	0	0	0	0	0	0	3	3%	300	1%	0.0	0%
1.4.2 Condenser subassembly	0	1	1	0	0	0	0	0	0	0	0	6	7%	2200	8%	0.5	1%
1.4.3 Refrigerant	0	0	0	0	0	0	0	1	1	1	1	4	4%	2000	7%	0.3	0%
Sum	1	2	2	3	2	2	1	3	3	1	1	92	100%	27525	100%	9.0	100%
%	1%	2%	2%	3%	2%	2%	1%	3%	3%	1%	1%	100%					

Figure B.4 Components to Components Parameters Matrix – Primary Level Matrix

Component Parameters x Test Measures		Electrical damage	Physical damage	Vibration amplitude	Vibration frequency	Failure of component in oil transport assembly	engine coolant transport assembly	Bursting of component in oil transport assembly	engine coolant transport assembly	Presence of corrosion in any component	Presence of leaks from any component	Heat transferred from engine	Heat transferred to/from transmission	Heat transferred from cabin	Presense of sharp edges	Presense of hot surfaces	Sum	%
Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) þ	Direction to change Cpt. Param. to decrease mass (+1 = up, -1 = down, 0 = unclear) ò	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	1	1	1	-1	-1		
Max thermal power dissipation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Max electrical power draw	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-4%
Solid volume	-1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	-1	2	7%
Liquid volume	-1	0	0	1	1	0	0	-1	-1	0	-1	0	0	0	0	0	-1	-4%
Average density	-1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	2	7%
Max air flow produced	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	3	11%
Max torque delivered	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Depth	-1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	-1	1	4%
Diameter	-1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	-1	1	4%
Number of blades	-1	0	0	1	1	0	0	0	0	0	0	0	0	0	-1	0	1	4%
Blade thickness	-1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	3	11%
Opening temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Front area	-1	0	0	0	0	0	0	0	0	-1	0	-1	-1	-1	0	-1	-5	-19%
Cooling fin area	1	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	4	15%
Thickness	-1	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	6	22%
Interior diameter	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Length	-1	0	-1	1	1	0	0	0	0	0	0	0	0	0	0	-1	0	0%
Max flow rate delivered	1	0	0	0	0	0	0	1	1	0	0	1	1	1	0	0	5	19%
Thermal capacitance as liquid	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	3	11%
Density as liquid	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Thermal capacitance as vapor	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	3	11%
Density as vapor	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Sum		-1	0	9	9	1	1	1	1	0	-1	4	4	4	0	-5	27	100%
%		-4%	0%	33%	33%	4%	4%	4%	4%	0%	-4%	15%	15%	15%	0%	-19%	100%	

Figure B.5 Component Parameters to Test Measures Matrix – Primary Level Matrix

Test Measures x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF	7. Burst pressure test for coolant	8. Corrosion test	9. Leak test	10. Heat transfer from engine test	11. Heat transfer from transmission test	12. Heat transfer from cabin test	13. User safety test	Sum	%
Electrical damage	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	6%
Physical damage	1	1	0	0	0	0	0	0	0	0	0	0	0	**2**	13%
Vibration amplitude	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**	6%
Vibration frequency	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**	6%
Failure of component in oil transport assembly	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**	6%
Failure of component in engine coolant transport assembly	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**	6%
Bursting of component in oil transport assembly	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**	6%
Bursting of component in engine coolant transport assembly	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	6%
Presence of corrosion in any component	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**	6%
Presence of leaks from any component	0	0	0	0	0	0	0	0	1	0	0	0	0	**1**	6%
Heat transferred from engine	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**	6%
Heat transferred to/from transmission	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**	6%
Heat transferred from cabin	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**	6%
Presense of sharp edges	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**	6%
Presense of hot surfaces	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**	6%
Sum	**2**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**16**	100%
%	13%	6%	13%	6%	6%	6%	6%	6%	6%	6%	6%	6%	13%	100%	

Figure B.6 Test Measures to Tests Matrix – Primary Level Matrix

CommandButton3 Requirements x Working Principles	take advantage of speed of outside air relative to vehicle speed	force air	forced transport	mechanical orifice	electrical signal	forced convection	thermal capacitance	closed container	rigid connection	electrical insulation	counterbalance	non-corroding materials	shield corroding materials	tight connections	impervious to punctures	round edges	sheild sharp edges	keep surfaces cool	shield hot surfaces	Sum	%
1.1 maintain engine temperature within operating range	1	2	4	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	13	33%
1.2 maintain transmission temperature within operating range	0	0	2	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	4	10%
1.3 maintain cabin temperature within comfort range	1	2	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	6	15%
2.1 pass wading depth test without failure	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2	5%
2.2 pass acceleration test without failure	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3	8%
2.3 pass vibration test without failure	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	2	5%
2.4 pass corrosion test without failure	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2	5%
2.5 not fail under excess pressure	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
3.1 not leak fluids into the environment	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	2	5%
4.1 prevent injuring the user	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	4	10%
5.1 be secured to the vehicle frame	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	3%
Minimum clearance to engine mounted components in X-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted components in Y-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted components in Z-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick fit connectors for all hoses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mix-up proof hose connections	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Assembly vertically from underneath should be with a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Vacuum assisted filling process for engine coolant would be	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Ambient temperatures outside the vehicle should be -40°C to	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Coolant temperatures must be -40°C to +140°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures should be 18mbara to 3.5bara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use of common parts internally and externally for	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must be of Uniform periphery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use closed air ducting for cooling system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must have mounting brackets for module to include thermostat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh ca. 26dm2 (580mm x 449mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mesh depth max. 30mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Optional low temperature radiator for automatic transmission ca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak rate 150 l/min at 300mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
In- and outlet should be with a nominal width (NW) 32mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Bleeding outlet (integrated in inlet connector) should be NW 12r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Overflow outlet should be NW 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Dimensions of oil cooler's block size X=45mm; Y=165mm; Z=80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick connectors for transmission fluid and engine coolant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Operating pressures transmission fluid should be in the range c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures engine coolant should be in the range of 3bara at –40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for transmission fluid is minimum 20barg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for engine coolant is minimum 2,5barg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh of condenser should be 22.2dm2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Sum	2	4	6	2	1	3	3	2	7	1	1	1	1	1	1	1	1	1	1	40	100%
%	5%	10%	15%	5%	3%	8%	8%	5%	18%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	100%	

Figure B.7 Requirements to Working Principle Matrix – Secondary Level Matrix

Functions x Components	1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	tank subassembly	1.2.3 Radiator cap	1.2.4 Radiator subassembly	1.2.5 Left bracket	1.2.6 Right bracket	1.2.7 Inlet water hose	1.2.8 Outlet water hose	1.2.9 Temperature sensor	1.2.10 Water pump subassembly	1.2.11 Engine coolant	1.3 Transmission oil transport assembly	liquid heat exchanger subassembly	1.3.2 Transmission oil	1.4 Refrigerant transport assembly	1.4.1 Drying container	1.4.2 Condenser subassembly	1.4.3 Refrigerant	Sum	%
1.1.1 transport air across the engine coolant transport assembly	2	2	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	3%
1.1.1.1 Turn the fan when activated by the computer	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	2%
1.1.2 transport coolant from the engine	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	5	2%
1.1.2.1 Allow engine coolant to pass through if above a certain	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1%
1.1.2.2 Not allow engine coolant to pass through if below a certain	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1%
1.1.2.3 Send a signal to the computer indicating the engine coolant	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	1%
1.1.2.4 Pump engine coolant through the engine coolant transport	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	5	2%
1.1.3 allow heat to escape from coolant to the air	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	7	3%
1.1.3.1 Store heat absorbed from the engine	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	1	7	3%
1.1.4 transport coolant back to the engine	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	5	2%
1.1.4.1 store excess engine coolant	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	6	2%
1.1.4.2 Pump engine coolant through the engine coolant transport	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	5	2%
1.1.5 allow engine coolant to be added	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
1.2.1 transport oil from the transmission	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	5	2%
1.2.2 allow heat to transfer to/from the engine coolant	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	7	3%
1.2.2.1 Store heat absorbed from the transmission	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	1	7	3%
1.2.3 transport oil back to the transmission	1	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	5	2%
1.3.1 transport air across the refrigerant transport assembly	2	2	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	3%
1.3.1.1 Turn the fan when activated by the computer	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	2%
1.3.2 allow heat to escape from refrigerant to the air	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	1	0	7	3%
1.3.2.1 Store water trapped in the refrigerant transport assembly	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	6	2%
1.3.2.2 Store heat absorbed from the cabin	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	1	7	3%
2.1.1 Carry ### forces exerted by water	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
2.1.2 Not short electronics from water	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5	2%
2.2.1 Carry ### forces from x direction acceleration	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
2.2.2 Carry ### forces from y direction acceleration	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
2.2.3 Carry ### forces from z direction acceleration	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
2.3.1 Carry ### forces from other vibrating components	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
2.3.2 Balance the fan to prevent vibrations	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1%
2.4.1 Do not corrode in the presence of water, salt, etc.	2	2	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	0	1	1	0	2	1	2	0	33	13%
2.5.1 Carry ### forces from pressurizing system	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
3.1.1 Do not leak fluids into the neviroment	2	0	0	0	0	0	2	2	2	2	2	0	0	2	2	1	2	0	2	2	0	2	2	0	0	27	10%
4.1.1 Prevent cutting the user	2	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	7	3%
4.1.2 Prevent burning the user	2	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	2%
5.1.1 Transmit forces to the vehicle frame	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
Sum	40	11	7	6	2	9	30	6	5	6	15	8	8	9	9	4	11	3	16	13	3	20	6	12	3	262	100%
%	15%	4%	3%	2%	1%	3%	11%	2%	2%	2%	6%	3%	3%	3%	3%	2%	4%	1%	6%	5%	1%	8%	2%	5%	1%	100%	

Figure B.8 Functions to Components Matrix – Secondary Level Matrix

Working Principles x Component Parameters	Max thermal power dissipation	Max electrical power draw	Solid volume	Liquid volume	Average density	Max air flow produced	Max torque delivered	Depth	Diameter	Number of blades	Blade thickness	Opening temperature	Front area	Cooling fin area	Thickness	Interior diameter	Length	Max flow rate delivered	Thermal capacitance as liquid	Density as liquid	Thermal capacitance as vapor	Density as vapor	Sum	%
take advantage of speed of outs	1	2	2	1	3	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**12**	2%
force air	1	3	2	1	5	1	1	3	3	1	1	0	0	0	0	0	0	0	0	0	0	0	**22**	4%
forced transport	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	4%
mechanical orifice	2	2	3	2	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**13**	2%
electrical signal	2	2	3	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**12**	2%
forced convection	4	3	7	7	7	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**34**	6%
thermal capacitance	4	3	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	1	**27**	5%
closed container	3	2	6	5	6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**23**	4%
rigid connection	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	7%
electrical insulation	2	5	3	2	5	1	1	2	2	0	0	0	0	0	0	0	0	1	0	0	0	0	**24**	5%
counterbalance	1	2	3	1	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**11**	2%
non-corroding materials	4	6	16	9	22	1	1	6	4	1	1	1	2	2	3	2	2	1	0	0	0	0	**84**	16%
shield corroding materials	3	5	9	5	11	1	1	4	2	0	0	1	2	2	0	0	0	1	0	0	0	0	**47**	9%
tight connections	4	4	11	8	14	0	0	2	1	0	0	1	1	1	3	2	2	1	0	0	0	0	**55**	10%
impervious to punctures	4	4	10	8	13	0	0	2	1	0	0	1	1	1	3	2	2	1	0	0	0	0	**53**	10%
round edges	2	1	3	3	4	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**15**	3%
sheild sharp edges	1	2	2	1	3	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**12**	2%
keep surfaces cool	1	1	1	1	2	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	**10**	2%
shield hot surfaces	2	2	3	3	3	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	**16**	3%
Sum	**47**	**55**	**99**	**72**	**125**	**7**	**4**	**29**	**18**	**3**	**3**	**5**	**11**	**11**	**12**	**8**	**8**	**6**	**3**	**3**	**1**	**1**	**531**	100%
%	9%	10%	19%	14%	24%	1%	1%	5%	3%	1%	1%	1%	2%	2%	2%	2%	2%	1%	1%	1%	0%	0%	100%	

Figure B.9 Working Principles to Components Parameters Matrix – Secondary Level Matrix

Components x Test Measures	Electrical damage	Physical damage	Vibration amplitude	Vibration frequency	Failure of component in oil transport assembly	Failure of component in engine coolant transport assembly	Bursting of component in oil transport assembly	Bursting of component in engine coolant transport assembly	corrosion in any component	Presence of leaks from any component	Heat transferred from engine	Heat transferred to/from transmission	Heat transferred from cabin	Presense of sharp edges	Presense of hot surfaces	Sum	%
1. Cooling system	-1	1	3	3	0	0	-1	-1	0	-1	0	0	0	0	-1	**2**	2%
1.1 Air transport assembly	-1	1	2	2	0	0	0	0	0	0	1	1	1	0	-1	**6**	5%
1.1.1 Motor subassembly	-1	0	3	3	0	0	0	0	0	0	0	0	0	0	-2	**3**	3%
1.1.2 Fan	0	0	5	5	0	0	0	0	0	0	0	0	0	0	-2	**8**	7%
1.1.3 Counterweight	0	1	2	2	0	0	0	0	0	0	0	0	0	0	-1	**4**	4%
1.1.4 Fan shroud	0	0	3	3	0	0	0	0	0	0	0	0	0	0	-2	**4**	4%
1.2 Engine coolant transport ass	-1	1	3	3	0	0	-1	-1	0	-1	0	0	0	0	-1	**2**	2%
1.2.1 Thermostat	0	1	2	2	0	0	0	0	0	0	0	0	0	0	-1	**4**	4%
1.2.2 Expansion tank subassem	0	1	4	4	1	1	0	0	0	-1	0	0	0	0	-1	**9**	8%
1.2.3 Radiator cap	0	1	2	2	0	0	0	0	0	0	0	0	0	0	-1	**4**	4%
1.2.4 Radiator subassembly	0	1	4	4	0	0	-1	-1	0	-1	0	0	0	0	-3	**3**	3%
1.2.5 Left bracket	0	1	2	2	0	0	0	0	0	0	0	0	0	0	-1	**4**	4%
1.2.6 Right bracket	0	1	2	2	0	0	0	0	0	0	0	0	0	0	-1	**4**	4%
1.2.7 Inlet water hose	0	-1	3	3	1	1	1	1	0	0	0	0	0	0	-1	**8**	7%
1.2.8 Outlet water hose	0	-1	3	3	1	1	1	1	0	0	0	0	0	0	-1	**8**	7%
1.2.9 Temperature sensor	0	1	2	2	0	0	0	0	0	0	0	0	0	0	-1	**4**	4%
1.2.10 Water pump subassembly	-1	0	3	3	0	0	1	1	0	0	1	1	1	0	-2	**8**	7%
1.2.11 Engine coolant	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	**3**	3%
1.3 Transmission oil transport a	-1	1	3	3	0	0	-1	-1	0	-1	0	0	0	0	-1	**2**	2%
1.3.1 Liquid-liquid heat exchang	0	1	3	3	0	0	-1	-1	0	-1	0	0	0	0	-1	**3**	3%
1.3.2 Transmission oil	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	**3**	3%
1.4 Refrigerant transport assem	0	1	3	3	0	0	-1	-1	0	-1	0	0	0	0	-1	**3**	3%
1.4.1 Drying container	0	1	3	3	0	0	-1	-1	0	-1	0	0	0	0	-1	**3**	3%
1.4.2 Condenser subassembly	0	1	4	4	0	0	-1	-1	0	-1	0	0	0	0	-3	**3**	3%
1.4.3 Refrigerant	0	0	0	0	0	0	0	0	0	0	2	2	2	0	0	**6**	5%
Sum	**-6**	**14**	**64**	**64**	**3**	**3**	**-5**	**-5**	**0**	**-9**	**6**	**6**	**6**	**0**	**-30**	**111**	100%
%	-5%	13%	58%	58%	3%	3%	-5%	-5%	0%	-8%	5%	5%	5%	0%	-27%	100%	

Figure B.10 Components to Test Measures Matrix – Secondary Level Matrix

Component Parameters x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF	7. Burst pressure test for coolant	8. Corrosion test	9. Leak test	10. Heat transfer from engine test	from transmission test	12. Heat transfer from cabin test	13. User safety test	Sum	%
Max thermal power dissipation	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Max electrical power draw	-1	0	0	0	0	0	0	0	0	0	0	0	0	**-1**	-4%
Solid volume	1	1	2	0	0	0	0	0	0	0	0	0	-1	**3**	11%
Liquid volume	0	0	2	0	0	-1	-1	0	-1	0	0	0	0	**-1**	-4%
Average density	0	0	2	0	0	0	0	0	0	0	0	0	0	**2**	7%
Max air flow produced	0	0	0	0	0	0	0	0	0	1	1	1	0	**3**	11%
Max torque delivered	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Depth	0	0	2	0	0	0	0	0	0	0	0	0	-1	**1**	4%
Diameter	0	0	2	0	0	0	0	0	0	0	0	0	-1	**1**	4%
Number of blades	0	0	2	0	0	0	0	0	0	0	0	0	-1	**1**	4%
Blade thickness	0	0	2	0	0	0	0	0	0	0	0	0	1	**3**	11%
Opening temperature	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Front area	0	0	0	0	0	0	0	-1	0	-1	-1	-1	-1	**-5**	-19%
Cooling fin area	0	0	0	0	0	0	0	1	0	1	1	1	0	**4**	15%
Thickness	0	0	2	1	1	1	1	0	0	0	0	0	0	**6**	22%
Interior diameter	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Length	-1	-1	2	0	0	0	0	0	0	0	0	0	-1	**-1**	-4%
Max flow rate delivered	0	0	0	0	0	1	1	0	0	1	1	1	0	**5**	19%
Thermal capacitance as liquid	0	0	0	0	0	0	0	0	0	1	1	1	0	**3**	11%
Density as liquid	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Thermal capacitance as vapor	0	0	0	0	0	0	0	0	0	1	1	1	0	**3**	11%
Density as vapor	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Sum	**-1**	**0**	**18**	**1**	**1**	**1**	**1**	**0**	**-1**	**4**	**4**	**4**	**-5**	**27**	100%
%	-4%	0%	67%	4%	4%	4%	4%	0%	-4%	15%	15%	15%	-19%	100%	

Figure B.11 Component Parameters to Tests Matrix – Secondary Level Matrix

Requirements x Components	1. Cooling system	1.1 Air transport assembly	1.1.1 Motor subassembly	1.1.2 Fan	1.1.3 Counterweight	1.1.4 Fan shroud	1.2 Engine coolant transport assembly	1.2.1 Thermostat	1.2.2 Expansion tank subassembly	1.2.3 Radiator cap	1.2.4 Radiator subassembly	1.2.5 Left bracket	1.2.6 Right bracket	1.2.7 Inlet water hose	1.2.8 Outlet water hose	1.2.9 Temperature sensor	1.2.10 Water pump subassembly	1.2.11 Engine coolant	1.3 Transmission oil transport assembly	1.3.1 Liquid-liquid heat exchanger subassembly	1.3.2 Transmission oil	1.4 Refrigerant transport assembly	1.4.1 Drying container	1.4.2 Condenser subassembly	1.4.3 Refrigerant	Sum	%
1.1 maintain engine temperature within operating range	13	3	2	2	0	3	10	2	1	1	1	0	0	4	4	1	4	1	2	1	1	3	1	1	1	62	24%
1.2 maintain transmission temperature within operating range	4	0	0	0	0	0	4	0	0	0	1	0	0	2	2	0	2	1	2	1	1	2	0	1	1	24	9%
1.3 maintain cabin temperature within comfort range	6	3	2	2	0	3	3	0	1	1	1	0	0	0	0	0	0	1	2	1	1	3	1	1	1	33	13%
2.1 pass wading depth test without failure	2	1	1	0	0	0	2	0	0	0	1	1	1	0	0	0	1	0	1	1	0	1	0	1	0	14	5%
2.2 pass acceleration test without failure	3	0	0	0	0	0	3	0	0	0	3	3	3	0	0	0	0	0	3	3	0	3	0	3	0	27	10%
2.3 pass vibration test without failure	2	1	0	0	1	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	12	5%
2.4 pass corrosion test without failure	2	2	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	0	1	1	0	2	1	2	0	33	13%
2.5 not fail under excess pressure	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
3.1 not leak fluids into the environment	2	0	0	0	0	0	2	2	2	2	2	0	0	2	2	1	2	0	2	2	0	2	2	0	0	27	10%
4.1 prevent injuring the user	4	1	0	1	0	2	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	12	5%
5.1 be secured to the vehicle frame	1	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	0	1	0	9	3%
Minimum clearance to engine mounted components in X-direction should be 30 mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted components in Y-direction should be 30 mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted components in Z-direction should be 20 mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick fit connectors for all hoses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mix-up proof hose connections	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Assembly vertically from underneath should be with a minimum clearance 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Vacuum assisted filling process for engine coolant would be 18mbara for 25seconds duration	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Ambient temperatures outside the vehicle should be -40°C to +120°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Coolant temperatures must be -40°C to +140°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures should be 18mbara to 3.5bara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use of common parts internally and externally for reduced development costs tooling investment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must be of Uniform periphery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use closed air ducting for cooling system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must have mounting brackets for module to include thermostat ur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh ca. 26dm2 (580mm x 449mm)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mesh depth max. 30mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Optional low temperature radiator for automatic transmission ca. 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak rate 150 l/min at 300mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
In- and outlet should be with a nominal width (NW) 32mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Bleeding outlet (integrated in inlet connector) should be NW 12mn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Overflow outlet should be NW 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Dimensions of oil cooler's block size X=45mm; Y=165mm; Z=80mr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick connectors for transmission fluid and engine coolant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Operating pressures transmission fluid should be in the range of 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures engine coolant should be in the range of 3bara at –40°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for transmission fluid is minimum 20barg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for engine coolant is minimum 2,5barg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh of condenser should be 22.2dm2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Sum	40	11	7	6	2	9	30	6	5	6	15	8	8	9	9	4	11	3	16	13	3	20	6	12	3	262	100%
%	15%	4%	3%	2%	1%	3%	11%	2%	2%	2%	6%	3%	3%	3%	3%	2%	4%	1%	6%	5%	1%	8%	2%	5%	1%	100%	

Figure B.12 Requirements to Components Matrix – Secondary Level Matrix

Functions x Components Parameters	Max thermal power dissipation	Max electrical power draw	Solid volume	Liquid volume	Average density	Max air flow produced	Max torque delivered	Depth	Diameter	Number of blades	Blade thickness	Opening temperature	Front area	Cooling fin area	Thickness	Interior diameter	Length	Max flow rate delivered	Thermal capacitance as liquid	Density as liquid	Thermal capacitance as vapor	Density as vapor	Sum	%
1.1.1 transport air across the engine coolant transport assembly	2	5	4	2	8	2	1	4	4	1	1	0	0	0	0	0	0	0	0	0	0	0	**34**	3%
1.1.1.1 Turn the fan when activated by the computer	1	3	2	1	5	1	1	3	3	1	1	0	0	0	0	0	0	0	0	0	0	0	**22**	2%
1.1.2 transport coolant from the engine	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	2%
1.1.2.1 Allow engine coolant to pass through if above a certain temperature	2	2	3	2	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**13**	1%
1.1.2.2 Not allow engine coolant to pass through if below a certain temperature	2	2	3	2	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**13**	1%
1.1.2.3 Send a signal to the computer indicating the engine coolant temperature	2	2	3	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**12**	1%
1.1.2.4 Pump engine coolant through the engine coolant transport assembly	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	2%
1.1.3 allow heat to escape from coolant to the air	4	3	7	7	7	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**34**	3%
1.1.3.1 Store heat absorbed from the engine	4	3	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	1	**27**	2%
1.1.4 transport coolant back to the engine	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	2%
1.1.4.1 store excess engine coolant	3	2	6	5	6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**23**	2%
1.1.4.2 Pump engine coolant through the engine coolant transport assembly	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	2%
1.1.5 allow engine coolant to be added	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1.2.1 transport oil from the transmission	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	2%
1.2.2 allow heat to transfer to/from the engine coolant	4	3	7	7	7	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**34**	3%
1.2.2.1 Store heat absorbed from the transmission	4	3	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	1	**27**	2%
1.2.3 transport oil back to the transmission	2	3	2	2	5	0	0	1	1	0	0	0	0	0	2	2	2	1	0	0	0	0	**23**	2%
1.3.1 transport air across the refrigerant transport assembly	2	5	4	2	8	2	1	4	4	1	1	0	0	0	0	0	0	0	0	0	0	0	**34**	3%
1.3.1.1 Turn the fan when activated by the computer	1	3	2	1	5	1	1	3	3	1	1	0	0	0	0	0	0	0	0	0	0	0	**22**	2%
1.3.2 allow heat to escape from refrigerant to the air	4	3	7	7	7	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**34**	3%
1.3.2.1 Store water trapped in the refrigerant transport assembly	3	2	6	5	6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**23**	2%
1.3.2.2 Store heat absorbed from the cabin	4	3	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	1	**27**	2%
2.1.1 Carry ### forces exerted by water	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
2.1.2 Not short electronics from water	2	5	3	2	5	1	1	2	2	0	0	0	0	0	0	0	0	1	0	0	0	0	**24**	2%
2.2.1 Carry ### forces from x direction acceleration	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
2.2.2 Carry ### forces from y direction acceleration	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
2.2.3 Carry ### forces from z direction acceleration	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
2.3.1 Carry ### forces from other vibrating components	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
2.3.2 Balance the fan to prevent vibrations	1	2	3	1	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**11**	1%
2.4.1 Do not corrode in the presence of water, salt, etc.	7	11	25	14	33	2	2	10	6	1	1	2	4	4	3	2	2	2	0	0	0	0	**131**	12%
2.5.1 Carry ### forces from pressurizing system	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
3.1.1 Do not leak fluids into the neviroment	8	8	21	16	27	0	0	4	2	0	0	2	2	2	6	4	4	2	0	0	0	0	**108**	10%
4.1.1 Prevent cutting the user	3	3	5	4	7	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	**27**	2%
4.1.2 Prevent burning the user	3	3	4	4	5	0	0	2	1	1	1	0	1	1	0	0	0	0	0	0	0	0	**26**	2%
5.1.1 Transmit forces to the vehicle frame	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	**38**	3%
Sum	**106**	**115**	**202**	**157**	**253**	**11**	**7**	**60**	**33**	**6**	**6**	**6**	**27**	**27**	**23**	**18**	**18**	**11**	**9**	**9**	**3**	**3**	**1110**	100%
%	10%	10%	18%	14%	23%	1%	1%	5%	3%	1%	1%	1%	2%	2%	2%	2%	2%	1%	1%	1%	0%	0%	100%	

Figure B.13 Functions to Component Parameters Matrix – Tertiary Level Matrix

Working Principles x Test Measures	Electrical damage	Physical damage	Vibration amplitude	Vibration frequency	in oil transport assembly	in engine coolant transport assembly	component in oil transport assembly	component in engine coolant transport	corrosion in any component	Presence of leaks from any component	Heat transferred from engine	Heat transferred to/from transmission	Heat transferred from cabin	Presense of sharp edges	Presense of hot surfaces	Sum	%
take advantage of speed of outs	-2	2	8	8	0	0	-1	-1	0	-1	1	1	1	0	-4	**12**	2%
force air	-3	2	16	16	0	0	-1	-1	0	-1	1	1	1	0	-8	**23**	5%
forced transport	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	6%
mechanical orifice	-2	3	8	8	0	0	-2	-2	0	-2	0	0	0	0	-3	**8**	2%
electrical signal	-2	3	8	8	0	0	-2	-2	0	-2	0	0	0	0	-3	**8**	2%
forced convection	-3	7	23	23	0	0	-7	-7	0	-7	0	0	0	0	-11	**18**	4%
thermal capacitance	-3	4	12	12	0	0	-4	-4	0	-4	4	4	4	0	-4	**21**	4%
closed container	-2	6	18	18	1	1	-4	-4	0	-5	0	0	0	0	-6	**23**	5%
rigid connection	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	5%
electrical insulation	-5	3	14	14	0	0	-1	-1	0	-2	2	2	2	0	-7	**21**	4%
counterbalance	-2	3	7	7	0	0	-1	-1	0	-1	1	1	1	0	-3	**12**	2%
non-corroding materials	-6	14	64	64	3	3	-5	-5	0	-9	2	2	2	0	-30	**99**	20%
shield corroding materials	-5	9	31	31	0	0	-4	-4	0	-5	2	2	2	0	-17	**42**	8%
tight connections	-4	9	41	41	3	3	-4	-4	0	-8	1	1	1	0	-17	**63**	13%
impervious to punctures	-4	8	39	39	3	3	-4	-4	0	-8	1	1	1	0	-16	**59**	12%
round edges	-1	3	12	12	0	0	-3	-3	0	-3	0	0	0	0	-5	**12**	2%
sheild sharp edges	-2	2	8	8	0	0	-1	-1	0	-1	1	1	1	0	-4	**12**	2%
keep surfaces cool	-1	1	8	8	0	0	-1	-1	0	-1	0	0	0	0	-3	**10**	2%
shield hot surfaces	-2	3	10	10	0	0	-3	-3	0	-3	0	0	0	0	-5	**7**	1%
Sum	**-55**	**91**	**369**	**369**	**12**	**12**	**-54**	**-54**	**0**	**-72**	**17**	**17**	**17**	**0**	**-165**	**504**	100%
%	-11%	18%	73%	73%	2%	2%	-11%	-11%	0%	-14%	3%	3%	3%	0%	-33%	100%	

Figure B.14 Working Principles to Test Measures Matrix – Tertiary Level Matrix

Components x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF	7. Burst pressure test for coolant	8. Corrosion test	9. Leak test	10. Heat transfer from engine test	from transmission test	12. Heat transfer from cabin test	13. User safety test	Sum	%
1. Cooling system	0	1	6	0	0	-1	-1	0	-1	0	0	0	-1	**3**	2%
1.1 Air transport assembly	0	1	4	0	0	0	0	0	0	1	1	1	-1	**7**	6%
1.1.1 Motor subassembly	-1	0	6	0	0	0	0	0	0	0	0	0	-2	**3**	2%
1.1.2 Fan	0	0	10	0	0	0	0	0	0	0	0	0	-2	**8**	6%
1.1.3 Counterweight	1	1	4	0	0	0	0	0	0	0	0	0	-1	**5**	4%
1.1.4 Fan shroud	0	0	6	0	0	0	0	0	0	0	0	0	-2	**4**	3%
1.2 Engine coolant transport ass	0	1	6	0	0	-1	-1	0	-1	0	0	0	-1	**3**	2%
1.2.1 Thermostat	1	1	4	0	0	0	0	0	0	0	0	0	-1	**5**	4%
1.2.2 Expansion tank subassem	1	1	8	1	1	0	0	0	-1	0	0	0	-1	**10**	8%
1.2.3 Radiator cap	1	1	4	0	0	0	0	0	0	0	0	0	-1	**5**	4%
1.2.4 Radiator subassembly	1	1	8	0	0	-1	-1	0	-1	0	0	0	-3	**4**	3%
1.2.5 Left bracket	1	1	4	0	0	0	0	0	0	0	0	0	-1	**5**	4%
1.2.6 Right bracket	1	1	4	0	0	0	0	0	0	0	0	0	-1	**5**	4%
1.2.7 Inlet water hose	-1	-1	6	1	1	1	1	0	0	0	0	0	-1	**7**	6%
1.2.8 Outlet water hose	-1	-1	6	1	1	1	1	0	0	0	0	0	-1	**7**	6%
1.2.9 Temperature sensor	1	1	4	0	0	0	0	0	0	0	0	0	-1	**5**	4%
1.2.10 Water pump subassembly	-1	0	6	0	0	1	1	0	0	1	1	1	-2	**8**	6%
1.2.11 Engine coolant	0	0	0	0	0	0	0	0	0	1	1	1	0	**3**	2%
1.3 Transmission oil transport a	0	1	6	0	0	-1	-1	0	-1	0	0	0	-1	**3**	2%
1.3.1 Liquid-liquid heat exchang	1	1	6	0	0	-1	-1	0	-1	0	0	0	-1	**4**	3%
1.3.2 Transmission oil	0	0	0	0	0	0	0	0	0	1	1	1	0	**3**	2%
1.4 Refrigerant transport assem	1	1	6	0	0	-1	-1	0	-1	0	0	0	-1	**4**	3%
1.4.1 Drying container	1	1	6	0	0	-1	-1	0	-1	0	0	0	-1	**4**	3%
1.4.2 Condenser subassembly	1	1	8	0	0	-1	-1	0	-1	0	0	0	-3	**4**	3%
1.4.3 Refrigerant	0	0	0	0	0	0	0	0	0	2	2	2	0	**6**	5%
Sum	**8**	**14**	**128**	**3**	**3**	**-5**	**-5**	**0**	**-9**	**6**	**6**	**6**	**-30**	**125**	100%
%	6%	11%	102%	2%	2%	-4%	-4%	0%	-7%	5%	5%	5%	-24%	100%	

Figure B.14 Components to Tests Matrix – Tertiary Level Matrix

Requirements x Component Parameters	Max thermal power dissipation	Max electrical power draw	Solid volume	Liquid volume	Average density	Max air flow produced	Max torque delivered	Depth	Diameter	Number of blades	Blade thickness	Opening temperature	Front area	Cooling fin area	Thickness	Interior diameter	Length	Max flow rate delivered	Thermal capacitance as liquid	Density as liquid	Thermal capacitance as vapor	Density as vapor	Sum	%
1.1 maintain engine temperature within operating	28	34	40	33	59	3	2	13	11	2	2	2	2	2	9	8	8	4	3	3	1	1	270	24%
1.2 maintain transmission temperature within	12	12	15	15	21	0	0	4	2	0	0	0	2	2	4	4	4	2	3	3	1	1	107	10%
1.3 maintain cabin temperature within comfort	14	16	23	19	30	3	2	9	7	2	2	0	2	2	1	0	0	0	3	3	1	1	140	13%
2.1 pass wading depth test without failure	6	8	12	9	14	1	1	4	2	0	0	0	2	2	0	0	0	1	0	0	0	0	62	6%
2.2 pass acceleration test without failure	12	9	27	21	27	0	0	6	0	0	0	0	6	6	0	0	0	0	0	0	0	0	114	10%
2.3 pass vibration test without failure	5	5	12	8	12	1	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	49	4%
2.4 pass corrosion test without failure	7	11	25	14	33	2	2	10	6	1	1	2	4	4	3	2	2	2	0	0	0	0	131	12%
2.5 not fail under excess pressure	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	38	3%
3.1 not leak fluids into the environment	8	8	21	16	27	0	0	4	2	0	0	2	2	2	6	4	4	2	0	0	0	0	108	10%
4.1 prevent injuring the user	6	6	9	8	12	1	0	4	3	1	1	0	1	1	0	0	0	0	0	0	0	0	53	5%
5.1 be secured to the vehicle frame	4	3	9	7	9	0	0	2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	38	3%
Minimum clearance to engine mounted	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Minimum clearance to engine mounted	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick fit connectors for all hoses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mix-up proof hose connections	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Assembly vertically from underneath should be	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Vacuum assisted filling process for engine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Ambient temperatures outside the vehicle should	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Coolant temperatures must be -40°C to +140°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures should be 18mbara to 3.5bara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use of common parts internally and	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must be of Uniform periphery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Should use closed air ducting for cooling system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Must have mounting brackets for module to inclu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh ca. 26dm2 (580mm x 44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Mesh depth max. 30mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Optional low temperature radiator for automatic tr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak rate 150 l/min at 300mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
In- and outlet should be with a nominal width (NW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Bleeding outlet (integrated in inlet connector) sho	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Overflow outlet should be NW 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Dimensions of oil cooler's block size X=45mm; Y=	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Quick connectors for transmission fluid and engi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Operating pressures transmission fluid should be	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Pressures engine coolant should be in the range	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for transmission fluid is minimu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Leak proof tests for engine coolant is minimum 2,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Total frontal area of mesh of condenser should be	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
Sum	106	115	202	157	253	11	7	60	33	6	6	6	27	27	23	18	18	11	9	9	3	3	1110	100%
%	10%	10%	18%	14%	23%	1%	1%	5%	3%	1%	1%	1%	2%	2%	2%	2%	2%	1%	1%	1%	0%	0%	100%	

Figure B.15 Requirements to Component Parameters Matrix – Fourth Level Matrix

Functions x Test Measures	Electrical damage	Physical damage	Vibration amplitude	Vibration frequency	Failure of component in oil transport assembly	in engine coolant transport assembly	component in oil transport assembly	component in engine coolant transport	corrosion in any component	Presence of leaks from any component	Heat transferred from engine	Heat transferred to/from transmission	Heat transferred from cabin	Presense of sharp edges	Presense of hot surfaces	Sum	%
1.1.1 transport air across the engine coolant	-5	4	24	24	0	0	-2	-2	0	-2	2	2	2	0	-12	**35**	4%
1.1.1.1 Turn the fan when activated by the	-3	2	16	16	0	0	-1	-1	0	-1	1	1	1	0	-8	**23**	2%
1.1.2 transport coolant from the engine	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	3%
1.1.2.1 Allow engine coolant to pass through if	-2	3	8	8	0	0	-2	-2	0	-2	0	0	0	0	-3	**8**	1%
1.1.2.2 Not allow engine coolant to pass	-2	3	8	8	0	0	-2	-2	0	-2	0	0	0	0	-3	**8**	1%
1.1.2.3 Send a signal to the computer	-2	3	8	8	0	0	-2	-2	0	-2	0	0	0	0	-3	**8**	1%
1.1.2.4 Pump engine coolant through the	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	3%
1.1.3 allow heat to escape from coolant to the	-3	7	23	23	0	0	-7	-7	0	-7	0	0	0	0	-11	**18**	2%
1.1.3.1 Store heat absorbed from the engine	-3	4	12	12	0	0	-4	-4	0	-4	4	4	4	0	-4	**21**	2%
1.1.4 transport coolant back to the engine	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	3%
1.1.4.1 store excess engine coolant	-2	6	18	18	1	1	-4	-4	0	-5	0	0	0	0	-6	**23**	2%
1.1.4.2 Pump engine coolant through the	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	3%
1.1.5 allow engine coolant to be added	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1.2.1 transport oil from the transmission	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	3%
1.2.2 allow heat to transfer to/from the engine	-3	7	23	23	0	0	-7	-7	0	-7	0	0	0	0	-11	**18**	2%
1.2.2.1 Store heat absorbed from the	-3	4	12	12	0	0	-4	-4	0	-4	4	4	4	0	-4	**21**	2%
1.2.3 transport oil back to the transmission	-3	0	15	15	2	2	1	1	0	-2	1	1	1	0	-6	**28**	3%
1.3.1 transport air across the refrigerant	-5	4	24	24	0	0	-2	-2	0	-2	2	2	2	0	-12	**35**	4%
1.3.1.1 Turn the fan when activated by the	-3	2	16	16	0	0	-1	-1	0	-1	1	1	1	0	-8	**23**	2%
1.3.2 allow heat to escape from refrigerant to	-3	7	23	23	0	0	-7	-7	0	-7	0	0	0	0	-11	**18**	2%
1.3.2.1 Store water trapped in the refrigerant	-2	6	18	18	1	1	-4	-4	0	-5	0	0	0	0	-6	**23**	2%
1.3.2.2 Store heat absorbed from the cabin	-3	4	12	12	0	0	-4	-4	0	-4	4	4	4	0	-4	**21**	2%
2.1.1 Carry ### forces exerted by water	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
2.1.2 Not short electronics from water	-5	3	14	14	0	0	-1	-1	0	-2	2	2	2	0	-7	**21**	2%
2.2.1 Carry ### forces from x direction acceleratio	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
2.2.2 Carry ### forces from y direction acceleratio	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
2.2.3 Carry ### forces from z direction acceleratio	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
2.3.1 Carry ### forces from other vibrating compo	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
2.3.2 Balance the fan to prevent vibrations	-2	3	7	7	0	0	-1	-1	0	-1	1	1	1	0	-3	**12**	1%
2.4.1 Do not corrode in the presence of water, salt	-11	23	95	95	3	3	-9	-9	0	-14	4	4	4	0	-47	**141**	14%
2.5.1 Carry ### forces from pressurizing system	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
3.1.1 Do not leak fluids into the neviroment	-8	17	80	80	6	6	-8	-8	0	-16	2	2	2	0	-33	**122**	12%
4.1.1 Prevent cutting the user	-3	5	20	20	0	0	-4	-4	0	-4	1	1	1	0	-9	**24**	2%
4.1.2 Prevent burning the user	-3	4	18	18	0	0	-4	-4	0	-4	0	0	0	0	-8	**17**	2%
5.1.1 Transmit forces to the vehicle frame	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
Sum	**-115**	**184**	**758**	**758**	**23**	**23**	**-123**	**-123**	**0**	**-157**	**34**	**34**	**34**	**0**	**-340**	**990**	100%
%	-12%	19%	77%	77%	2%	2%	-12%	-12%	0%	-16%	3%	3%	3%	0%	-34%	100%	

Figure B.16 Functions to Test Measures Matrix – Fourth Level Matrix

Working Principles x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF	7. Burst pressure test for coolant	8. Corrosion test	9. Leak test	10. Heat transfer from engine test	11. Heat transfer from transmission test	12. Heat transfer from cabin test	13. User safety test	Sum	%
take advantage of speed of outs	0	2	16	0	0	-1	-1	0	-1	1	1	1	-4	**14**	2%
force air	-1	2	32	0	0	-1	-1	0	-1	1	1	1	-8	**25**	4%
forced transport	-3	0	30	2	2	1	1	0	-2	1	1	1	-6	**28**	5%
mechanical orifice	1	3	16	0	0	-2	-2	0	-2	0	0	0	-3	**11**	2%
electrical signal	1	3	16	0	0	-2	-2	0	-2	0	0	0	-3	**11**	2%
forced convection	4	7	46	0	0	-7	-7	0	-7	0	0	0	-11	**25**	4%
thermal capacitance	1	4	24	0	0	-4	-4	0	-4	4	4	4	-4	**25**	4%
closed container	4	6	36	1	1	-4	-4	0	-5	0	0	0	-6	**29**	5%
rigid connection	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13	**35**	6%
electrical insulation	-2	3	28	0	0	-1	-1	0	-2	2	2	2	-7	**24**	4%
counterbalance	1	3	14	0	0	-1	-1	0	-1	1	1	1	-3	**15**	3%
non-corroding materials	8	14	128	3	3	-5	-5	0	-9	2	2	2	-30	**113**	19%
shield corroding materials	4	9	62	0	0	-4	-4	0	-5	2	2	2	-17	**51**	9%
tight connections	5	9	82	3	3	-4	-4	0	-8	1	1	1	-17	**72**	12%
impervious to punctures	4	8	78	3	3	-4	-4	0	-8	1	1	1	-16	**67**	11%
round edges	2	3	24	0	0	-3	-3	0	-3	0	0	0	-5	**15**	3%
sheild sharp edges	0	2	16	0	0	-1	-1	0	-1	1	1	1	-4	**14**	2%
keep surfaces cool	0	1	16	0	0	-1	-1	0	-1	0	0	0	-3	**11**	2%
shield hot surfaces	1	3	20	0	0	-3	-3	0	-3	0	0	0	-5	**10**	2%
Sum	**36**	**91**	**738**	**12**	**12**	**-54**	**-54**	**0**	**-72**	**17**	**17**	**17**	**-165**	**595**	100%
%	6%	15%	124%	2%	2%	-9%	-9%	0%	-12%	3%	3%	3%	-28%	100%	

Figure B.17 Working Principles to Tests Matrix – Fourth Level Matrix

Requirements x Test Measures	Electrical damage	Physical damage	Vibration amplitude	Vibration frequency	in oil transport assembly	in engine coolant transport assembly	component in oil transport assembly	component in engine coolant transport	corrosion in any component	Presence of leaks from any component	Heat transferred from engine	Heat transferred to/from transmission	Heat transferred from cabin	Presense of sharp edges	Presense of hot surfaces	Sum	%
1.1 maintain engine temperature within operating	-34	32	177	177	9	9	-20	-20	0	-33	11	11	11	0	-74	**256**	26%
1.2 maintain transmission temperature within	-12	11	65	65	4	4	-9	-9	0	-15	6	6	6	0	-27	**95**	10%
1.3 maintain cabin temperature within comfort	-16	23	93	93	1	1	-18	-18	0	-19	7	7	7	0	-41	**120**	12%
2.1 pass wading depth test without failure	-8	12	41	41	0	0	-8	-8	0	-9	2	2	2	0	-20	**47**	5%
2.2 pass acceleration test without failure	-9	27	81	81	0	0	-21	-21	0	-21	0	0	0	0	-39	**78**	8%
2.3 pass vibration test without failure	-5	12	34	34	0	0	-8	-8	0	-8	1	1	1	0	-16	**38**	4%
2.4 pass corrosion test without failure	-11	23	95	95	3	3	-9	-9	0	-14	4	4	4	0	-47	**141**	14%
2.5 not fail under excess pressure	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
3.1 not leak fluids into the environment	-8	17	80	80	6	6	-8	-8	0	-16	2	2	2	0	-33	**122**	12%
4.1 prevent injuring the user	-6	9	38	38	0	0	-8	-8	0	-8	1	1	1	0	-17	**41**	4%
5.1 be secured to the vehicle frame	-3	9	27	27	0	0	-7	-7	0	-7	0	0	0	0	-13	**26**	3%
Minimum clearance to engine mounted	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Minimum clearance to engine mounted	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Minimum clearance to engine mounted	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Quick fit connectors for all hoses	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Mix-up proof hose connections	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Assembly vertically from underneath should be	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Vacuum assisted filling process for engine coolant	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Ambient temperatures outside the vehicle should	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Coolant temperatures must be -40°C to +140°C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Pressures should be 18mbara to 3.5bara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Should use of common parts internally and	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Must be of Uniform periphery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Should use closed air ducting for cooling system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Must have mounting brackets for module to include	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Total frontal area of mesh ca. 26dm2 (580mm x 449r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Mesh depth max. 30mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Optional low temperature radiator for automatic trar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Leak rate 150 l/min at 300mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
In- and outlet should be with a nominal width (NW) 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Bleeding outlet (integrated in inlet connector) shoul	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Overflow outlet should be NW 12mm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Dimensions of oil cooler's block size X=45mm; Y=16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Quick connectors for transmission fluid and engine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Operating pressures transmission fluid should be ir	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Pressures engine coolant should be in the range of	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Leak proof tests for transmission fluid is minimum 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Leak proof tests for engine coolant is minimum 2,5b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Total frontal area of mesh of condenser should be 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
Sum	**-115**	**184**	**758**	**758**	**23**	**23**	**-123**	**-123**	**0**	**-157**	**34**	**34**	**34**	**0**	**-340**	**990**	100%
%	-12%	19%	77%	77%	2%	2%	-12%	-12%	0%	-16%	3%	3%	3%	0%	-34%	100%	

Figure B.18 Requirements to Test Measures Matrix – Fifth Level Matrix

Functions x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF	7. Burst pressure test for coolant	8. Corrosion test	9. Leak test	10. Heat transfer from engine test	from transmission test	12. Heat transfer from cabin test	13. User safety test
1.1.1 transport air across the engine coolant	-1	4	48	0	0	-2	-2	0	-2	2	2	2	-12
1.1.1.1 Turn the fan when activated by the	-1	2	32	0	0	-1	-1	0	-1	1	1	1	-8
1.1.2 transport coolant from the engine	-3	0	30	2	2	1	1	0	-2	1	1	1	-6
1.1.2.1 Allow engine coolant to pass through if	1	3	16	0	0	-2	-2	0	-2	0	0	0	-3
1.1.2.2 Not allow engine coolant to pass through	1	3	16	0	0	-2	-2	0	-2	0	0	0	-3
1.1.2.3 Send a signal to the computer indicating	1	3	16	0	0	-2	-2	0	-2	0	0	0	-3
1.1.2.4 Pump engine coolant through the engine	-3	0	30	2	2	1	1	0	-2	1	1	1	-6
1.1.3 allow heat to escape from coolant to the air	4	7	46	0	0	-7	-7	0	-7	0	0	0	-11
1.1.3.1 Store heat absorbed from the engine	1	4	24	0	0	-4	-4	0	-4	4	4	4	-4
1.1.4 transport coolant back to the engine	-3	0	30	2	2	1	1	0	-2	1	1	1	-6
1.1.4.1 store excess engine coolant	4	6	36	1	1	-4	-4	0	-5	0	0	0	-6
1.1.4.2 Pump engine coolant through the engine	-3	0	30	2	2	1	1	0	-2	1	1	1	-6
1.1.5 allow engine coolant to be added	0	0	0	0	0	0	0	0	0	0	0	0	0
1.1.6 allow engine coolant to be drained	0	0	0	0	0	0	0	0	0	0	0	0	0
1.2.1 transport oil from the transmission	-3	0	30	2	2	1	1	0	-2	1	1	1	-6
1.2.2 allow heat to transfer to/from the engine	4	7	46	0	0	-7	-7	0	-7	0	0	0	-11
1.2.2.1 Store heat absorbed from the	1	4	24	0	0	-4	-4	0	-4	4	4	4	-4
1.2.3 transport oil back to the transmission	-3	0	30	2	2	1	1	0	-2	1	1	1	-6
1.3.1 transport air across the refrigerant transport	-1	4	48	0	0	-2	-2	0	-2	2	2	2	-12
1.3.1.1 Turn the fan when activated by the	-1	2	32	0	0	-1	-1	0	-1	1	1	1	-8
1.3.2 allow heat to escape from refrigerant to the	4	7	46	0	0	-7	-7	0	-7	0	0	0	-11
1.3.2.1 Store water trapped in the refrigerant	4	6	36	1	1	-4	-4	0	-5	0	0	0	-6
1.3.2.2 Store heat absorbed from the cabin	1	4	24	0	0	-4	-4	0	-4	4	4	4	-4
2.1.1 Carry ### forces exerted by water	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
2.1.2 Not short electronics from water	-2	3	28	0	0	-1	-1	0	-2	2	2	2	-7
2.2.1 Carry ### forces from x direction acceleration	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
2.2.2 Carry ### forces from y direction acceleration	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
2.2.3 Carry ### forces from z direction acceleration	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
2.3.1 Carry ### forces from other vibrating compone	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
2.3.2 Balance the fan to prevent vibrations	1	3	14	0	0	-1	-1	0	-1	1	1	1	-3
2.4.1 Do not corrode in the presence of water, salt, e	12	23	190	3	3	-9	-9	0	-14	4	4	4	-47
2.5.1 Carry ### forces from pressurizing system	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
3.1.1 Do not leak fluids into the neviroment	9	17	160	6	6	-8	-8	0	-16	2	2	2	-33
4.1.1 Prevent cutting the user	2	5	40	0	0	-4	-4	0	-4	1	1	1	-9
4.1.2 Prevent burning the user	1	4	36	0	0	-4	-4	0	-4	0	0	0	-8
5.1.1 Transmit forces to the vehicle frame	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13

Figure B.19 Functions to Tests Matrix – Fifth Level Matrix

Requirements x Tests	1. Wading depth test	2. Acceleration test	3. Vibration test	4. Pressure swell test for ATF	5. Pressure swell test for coolant	6. Burst pressure test for ATF	7. Burst pressure test for coolant	8. Corrosion test	9. Leak test	10. Heat transfer from engine test	from transmission test	12. Heat transfer from cabin test	13. User safety test
1.1 maintain engine temperature within operating	-2	32	354	9	9	-20	-20	0	-33	11	11	11	-74
1.2 maintain transmission temperature within	-1	11	130	4	4	-9	-9	0	-15	6	6	6	-27
1.3 maintain cabin temperature within comfort	7	23	186	1	1	-18	-18	0	-19	7	7	7	-41
2.1 pass wading depth test without failure	4	12	82	0	0	-8	-8	0	-9	2	2	2	-20
2.2 pass acceleration test without failure	18	27	162	0	0	-21	-21	0	-21	0	0	0	-39
2.3 pass vibration test without failure	7	12	68	0	0	-8	-8	0	-8	1	1	1	-16
2.4 pass corrosion test without failure	12	23	190	3	3	-9	-9	0	-14	4	4	4	-47
2.5 not fail under excess pressure	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13
3.1 not leak fluids into the environment	9	17	160	6	6	-8	-8	0	-16	2	2	2	-33
4.1 prevent injuring the user	3	9	76	0	0	-8	-8	0	-8	1	1	1	-17
5.1 be secured to the vehicle frame	6	9	54	0	0	-7	-7	0	-7	0	0	0	-13

Figure B.19 Requirements to Tests Matrix – Sixth Level Matrix

APPENDIX – C

Accelerator Pedal Module Matrices

Requirements x Functions	Receive foot driver force	Oppose foot force	Limit pedal position	Cut User	Transmit vibration	Measure position	Convert force to position	Compare position	Modify voltage	Receive current	Constrain Motion	Sum	%
Pedal must self return.	1	1	0	0	0	0	0	0	0	0	0	2	4%
See req. 1.	1	1	0	0	0	0	0	0	0	0	0	2	4%
If pedal breaks the pedal must not be operational	1	0	0	0	0	0	0	0	0	0	0	1	2%
If pedal breaks the pedal must be recognizable as broken	0	1	0	0	0	0	0	0	0	0	0	1	2%
Pedal angle generated by the actuating force must be limited	0	0	1	0	0	0	0	0	0	0	0	1	2%
Pedal angle should be in the range of 16o +/- 0.5o	0	0	1	0	0	0	0	0	0	0	0	1	2%
Re-entry point should be scheduled within first 0.50 pedal angle	1	1	0	0	0	1	1	0	0	0	0	4	8%
Slope of response on the pedal (i.e., spring stiffness) must be within 0.8N / ° and 1.1N / °	0	1	0	0	0	0	0	0	0	0	0	1	2%
Response force must be linear and within +/- 2 N of the response line from req. 5 from 0.5 ° to 13.5 °	0	1	0	0	0	0	0	0	0	0	0	1	2%
Force angle must exhibit clear hysteresis from 0 ° to 16 °	1	1	0	0	0	0	0	0	0	0	0	2	4%
The ascending force should be 30 % (+6 N / -3 N) of the descending force	1	1	0	0	0	0	0	0	0	0	0	2	4%
Surfaces and edges that may be touched during assembly or use many not exhibit sharp burrs	0	0	0	1	0	0	0	0	0	0	0	1	2%
APM may not radiate disturbing mechanical noises (airborne sounds or mechanical vibrations.	0	0	0	0	1	0	0	0	0	0	0	1	2%
Should not make noticeable sound when knocked.	0	0	0	0	1	0	0	0	0	0	0	1	2%
Pedal must not exhibit “stick slip effect” (instability in the force angle – response behavior)	0	1	0	0	0	0	1	0	0	0	0	2	4%
Pedal must not stick (by sticking or hooking)	0	0	1	0	0	0	1	0	0	0	0	2	4%
APM must not send a signal to the ECU against the driver’s wishes	0	0	0	0	0	1	1	1	1	0	0	4	8%
The sensor must be redundant w.r.t. output voltage	0	0	0	0	0	0	0	0	1	0	0	1	2%
Must use external voltage supply.	0	0	0	0	0	0	0	0	0	1	0	1	2%
Each measuring channel is to be operated from its own voltage supply	0	0	0	0	0	0	0	0	0	1	0	1	2%
The requirements of the output signals of the driving pedal module must be maintained at all operating temperatures and over the entire life span of the driving pedal module. The requirements refer to an electrical wiring output.	0	0	0	0	0	0	0	0	1	0	0	1	2%
APM must mount to car	1	1	0	0	0	0	0	0	0	0	1	3	6%
APM must fit rest of car	0	0	0	0	0	0	0	0	0	0	1	1	2%
Must maintain full functional ability over its expected life (5000 hrs, from -40 C to 80 C)	1	1	1	1	1	1	1	1	1	1	1	11	23%
Sum	8	11	4	2	3	3	5	2	4	3	3	48	100%
%	17%	23%	8%	4%	6%	6%	10%	4%	8%	6%	6%	100%	

Figure C.1 Requirements to Functions Matrix

Functions x Components	Pedal	Film hinge	Housing Lid	Screws (8)	Pedal arm	Cam w/ ball joint	Cable	Spings (2)	Cable retainer	Spring retainer	Damper	Bushing	Axial bushing	Potentiometer	Housing	Sum	%
Receive foot driver force	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	**3**	6%
Oppose foot force	1	1	0	0	1	1	1	1	1	1	0	1	1	0	1	**11**	22%
Limit pedal position	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**	2%
Cut User	1	0	1	0	1	0	0	0	0	0	0	0	0	1	1	**5**	10%
Transmit vibration	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	**14**	27%
Measure position	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**	2%
Convert force to position	1	1	0	0	1	1	1	1	1	1	0	1	1	0	1	**11**	22%
Compare position	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**	2%
Modify voltage	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**	2%
Receive current	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**	2%
Constrain Motion	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	**2**	4%
Sum	**5**	**4**	**2**	**2**	**4**	**3**	**3**	**3**	**3**	**3**	**1**	**3**	**3**	**5**	**7**	**51**	100%
%	10%	8%	4%	4%	8%	6%	6%	6%	6%	6%	2%	6%	6%	10%	14%	100%	
Mass	70.4	14.0	46.1	8.0	10.0	26.0	5.5	5.5	5.5	5.5	1.1	0.8	9.6	65.2	196.6	469.7	
% Mass	15%	3%	10%	2%	2%	6%	1%	1%	1%	1%	0%	0%	2%	14%	42%	100%	
Sum * % Mass	0.7	0.1	0.2	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.7	2.9	51.0	
% Sum * % Mass	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	6%	100%	

Figure C.2 Functions to Components Matrix

Components	Mass (grams)	%
Pedal	70.4	15%
Film hinge	14	3%
Housing Lid	46.05	10%
Screws (8)	8	2%
Pedal arm	10.02	2%
Cam w/ ball joint	26	6%
Cable	5.525	1%
Spings (2)	5.525	1%
Cable retainer	5.525	1%
Spring retainer	5.525	1%
Damper	1.05	0%
Bushing	0.8	0%
Axial bushing	9.55	2%
Potentiometer	65.15	14%
Housing	196.6	42%
Sum	**469.72**	100%

Figure C.3 Component Mass List

Components x Component Parameters	Pedal width	Pedal length	Pedal thickness	Pedal density	Pedal Modulus of elasticity	Hinge width	Hinge thickness	Hinge length	Hinge Modulus of elasticity	Hinge Density	Lid cross sectional area	Lid thickness	Lid Density	Lid Modulus of Elasticity	Screw Length	Screw Diameter	Screw Pitch	Screw Density	Pedal arm length	Pedal arm diameter	Pedal arm ball diameter	Pedal arm ball socket diameter	Pedal arm density	Pedal arm Modulus of Elasticity	Cam profile	Cam Inner diameter	Cam Width	Cam Density	Cam Modulus of elasticity	Cam Ball joint diameter	Cable length	Cable diameter	Cable Modulus of Elasticity	Cable Density
Pedal	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Film hinge	1	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Housing Lid	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Screws (8)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pedal arm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	1	0	0	0	0
Cam w/ ball joint	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1	1	1	0	0	0	0
Cable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Spings (2)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Cable retainer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spring retainer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Damper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bushing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Axial bushing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Potentiometer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Housing	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	2	1	1	1	1	2	1	1	1	1	2	1	1	1	3	1	1	1	1	1	2	2	1	1	1	1	1	1	1	2	2	2	1	1

Components x Component Parameters	Spring wire diameter	Spring length	Spring Coil radius	Spring Modulus of Elasticity	Spring Density	Cable Retainer Diameter	Cable Retainer Length	Cable Retainer MOE	Cable Retainer Density	Spring retainter Diameter	Spring retainter Length	Spring retainter MOE	Spring retainter Density	Damper Diameter	Damper Length	Damper Material density	Damper Material durometer	Bushing Inner diameter	Bushing Outer diameter	Bushing Thickness	Bushing Density	Axial Bushing Inner diameter	Axial Bushing Outer Diameter	Axial Bushing Density	Axial Bushing thickness	Axial Bushing Ultimate tensile strengh	Axial Bushing Hardness	Pot. Diameter	Pot. Height	Pot. Density	Housing cross sectional area	Housing width	Housing wall thickness	Housing density	Housing Modulus of Elasticity	Sum	%
Pedal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	7%
Film hinge	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	7%
Housing Lid	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	6	7%
Screws (8)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5%
Pedal arm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	8%
Cam w/ ball joint	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	10	12%
Cable	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	7%
Spings (2)	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	8%
Cable retainer	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5%
Spring retainer	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5%
Damper	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5%
Bushing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	5%
Axial bushing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	6	7%
Potentiometer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	3	3%
Housing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	9	10%
Sum	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	3	1	1	1	1	1	1	1	1	2	1	1	1	1	86	100%
%	1%	2%	2%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	2%	2%	1%	1%	3%	1%	1%	1%	1%	1%	1%	1%	1%	2%	1%	1%	1%	1%	100%	

Figure C.4 Component to Component Parameters List

Component Parameters x Test Measures	"If the component parameter is changed in the direction indicated to reduce mass, what will be the effect on the test measure?" (+1 = T.M. increases, -1 = T.M. decreases, 0 = no effect or ambiguous effect on T.M.) ø	Permanent deformation	Malfunctioning	Breakage	Cracks	Squeaking or creaking noises	Existence of organic coatings	EM disruption of other systems	Rattling noises	Pedal sticking or hooking	Existence of corrosion	Conductivity of contacts	Resistivity of parts	Electical damage	Output pedal signal	Sum	%
Direction to change Cpt. Param. to decrease mass (+1 = up, -1 = down, 0 = unclear) ò	**Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) Þ**	**-1**	**-1**	**-1**	**-1**	**-1**	**0**	**-1**	**-1**	**-1**	**-1**	**0**	**1**	**-1**	**0**		
-1	**Pedal width**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Pedal length**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Pedal thickness**	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**4**	4%
-1	**Pedal density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Pedal Modulus of elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Hinge width**	0	1	1	1	0	0	0	0	0	0	0	0	0	0	**3**	3%
-1	**Hinge thickness**	0	1	1	1	0	0	0	0	0	0	0	0	0	0	**3**	3%
-1	**Hinge length**	0	1	1	1	0	0	0	0	0	0	0	0	0	0	**3**	3%
0	**Hinge Modulus of elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Hinge Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Lid cross sectional area**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Lid thickness**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Lid Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Lid Modulus of Elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Screw Length**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Screw Diameter**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
0	**Screw Pitch**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1	**Screw Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Pedal arm length**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Pedal arm diameter**	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**4**	4%
-1	**Pedal arm ball diameter**	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Pedal arm ball socket diameter**	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Pedal arm density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Pedal arm Modulus of Elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	**Cam profile**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	**Cam Inner diameter**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Cam Width**	0	1	1	0	0	0	0	0	0	0	0	0	0	0	**2**	2%
-1	**Cam Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Cam Modulus of elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Cam Ball joint diameter**	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Cable length**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Cable diameter**	1	1	1	0	0	0	0	0	0	0	0	0	0	0	**3**	3%
0	**Cable Modulus of Elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%

Figure C.5 Component to Component Parameters Matrix

Component Parameters x Test Measures	"If the component parameter is changed in the direction indicated to reduce mass, what will be the effect on the test measure?" (+1 = T.M. increases, -1 = T.M. decreases, 0 = no effect or ambiguous effect on T.M.) ø	Permanent deformation	Malfunctioning	Breakage	Cracks	Squeaking or creaking noises	Existence of organic coatings	EM disruption of other systems	Rattling noises	Pedal sticking or hooking	Existence of corrosion	Conductivity of contacts	Resistivity of parts	Electical damage	Output pedal signal	Sum	%
Direction to change Cpt. Param. to decrease mass (+1 = up, -1 = down, 0 = unclear) ò	**Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) þ**	**-1**	**-1**	**-1**	**-1**	**-1**	**0**	**-1**	**-1**	**-1**	**-1**	**0**	**1**	**-1**	**0**		
-1	**Cable Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Spring wire diameter**	1	1	1	0	0	0	0	0	0	0	0	0	0	0	**3**	3%
-1	**Spring length**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**1**	1%
-1	**Spring Coil radius**	1	1	1	0	0	0	0	0	0	0	0	0	0	0	**3**	3%
0	**Spring Modulus of Elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Spring Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Cable Retainer Diameter**	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**4**	4%
-1	**Cable Retainer Length**	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**4**	4%
0	**Cable Retainer MOE**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Cable Retainer Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Spring retainter Diameter**	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**4**	4%
-1	**Spring retainter Length**	1	1	1	1	0	0	0	0	0	0	0	0	0	0	**4**	4%
0	**Spring retainter MOE**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Spring retainter Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Damper Diameter**	0	1	0	0	1	0	0	0	1	0	0	0	0	0	**3**	3%
-1	**Damper Length**	0	1	0	0	1	0	0	0	1	0	0	0	0	0	**3**	3%
-1	**Damper Material density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Damper Material durometer**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	**Bushing Inner diameter**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Bushing Outer diameter**	1	1	1	1	1	0	0	0	0	0	0	0	0	0	**5**	5%
-1	**Bushing Thickness**	1	1	1	1	1	0	0	0	0	0	0	0	0	0	**5**	5%
-1	**Bushing Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Axial Bushing Inner diameter**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Axial Bushing Outer Diameter**	1	1	1	1	1	0	0	0	0	0	0	0	0	0	**5**	5%
-1	**Axial Bushing Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Axial Bushing thickness**	1	1	1	1	1	0	0	0	0	0	0	0	0	0	**5**	5%
0	**Axial Bushing Ultimate tensile strengh**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	**Axial Bushing Hardness**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Pot. Diameter**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Pot. Height**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Pot. Density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
-1	**Housing cross sectional area**	1	1	1	1	1	0	0	1	0	0	0	0	0	0	**6**	6%
-1	**Housing width**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	**Housing wall thickness**	1	1	1	1	1	0	0	0	0	0	0	0	0	0	**5**	5%
-1	**Housing density**	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**	1%
0	**Housing Modulus of Elasticity**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
	Sum	**15**	**28**	**19**	**15**	**11**	**0**	**0**	**16**	**2**	**0**	**0**	**0**	**0**	**0**	**106**	100%
	%	14%	26%	18%	14%	10%	0%	0%	15%	2%	0%	0%	0%	0%	0%	100%	

Figure C.5 Component to Component Parameters Matrix (Continued)

Test Measures x Tests	Static Test (QV 35 001)	Endurance Test (QV 35 001)	Metallic Parts Coating Test (GS 90011)	Compatibility Test (GS 97064-2)	Acoustic Behavior Test (GS 97064-1)	Abuse Test (GS 97064-2)	Corrosion Test (GS 97064-2)	Conductivity Test (97064-2)	Electrical Insulation Test (GS 97064-2)	High Voltage Test (GS 97064-2)	Short Circuit Test (GS 97064-2)	Sum	%
Permanent deformation	1	1	0	0	0	1	0	0	0	0	0	**3**	10%
Malfunctioning	1	1	0	0	0	1	0	0	0	0	0	**3**	10%
Breakage	1	1	0	0	0	1	0	0	0	0	0	**3**	10%
Cracks	1	1	0	0	0	1	0	0	0	0	0	**3**	10%
Squeaking or creaking noises	0	1	0	0	1	0	0	0	0	0	0	**2**	7%
Existence of organic coatings	0	0	1	0	0	0	0	0	0	0	0	**1**	3%
EM disruption of other systems	0	0	0	1	0	0	0	0	0	0	0	**1**	3%
Rattling noises	0	0	0	0	1	0	0	0	0	0	0	**1**	3%
Pedal sticking or hooking	1	1	0	0	0	1	0	0	0	0	0	**3**	10%
Existence of corrosion	0	0	0	0	0	0	1	0	0	0	0	**1**	3%
Conductivity of contacts	0	0	0	0	0	0	0	1	0	0	0	**1**	3%
Resistivity of parts	0	0	0	0	0	0	0	0	1	0	0	**1**	3%
Electical damage	0	0	0	0	0	0	0	0	0	1	1	**2**	7%
Output pedal signal	0	1	0	0	0	1	0	0	0	1	1	**4**	14%
Sum	**5**	**7**	**1**	**1**	**2**	**6**	**1**	**1**	**1**	**2**	**2**	**29**	100%
%	17%	24%	3%	3%	7%	21%	3%	3%	3%	7%	7%	100%	

Figure C.6 Test Measures to Tests Matrix

APPENDIX – D

Matrices for BMW 1 Series Seat Case Study

Functions x Components	120. Seat	120.1 Headrest assembly	120.2 Seat backrest assembly	120.2.1 Seat backrest cover	120.2.2 Side airbag sub-assembly	120.2.3 Backrest cover	120.2.4 Backrest foam	120.2.5 Side airbag housing	support sub-assembly	120.2.7 Backrest wire frame	120.2.8 Backrest frame	Seat Base	Seat Base Controls Trim Cover	Adjustable Thigh Support Assembly	Seat Base Cover	Seat Base Foam	Seat Pan	Seat Springs	Rear Seat Base Spring Bracket	Seat Base Frame Assembly	Left Slider/Rail Assembly	Right Slider/Rail Assembly	Adjustment Activation Lever	Seat Base Frame Members	Backrest Angle Adjustment Assembly	Seat Base Angle Adjustment Assembly	Main Height Adjustment Assembly	Seat Belt Mount & Pretensioner	Sum	%
Support person	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Protect user from crashes and bumps	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Support head	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Support back	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Protect rear passenger	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Insulate front passenger from rear passenger	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Prevent wear	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Transfer load to backrest	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Protect user	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5%
Aesthetics	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	7%
Protect foam	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Absorb energy	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Contain airbag	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Adjustability to support different people's lower backs	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Deform elastically	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Transfer load	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	0	1	0	0	0	0	6	14%
Support user weight	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Support legs	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
Allow adjustment	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	5%
Absorb energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	2%
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
deform elastically	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	2%
protect user from bumps	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	2%
transfer load from seat springs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	2%
allow space for rear passenger's feet	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	2%
allow forward and rearward adjustment and locking	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2	5%
activate forward and rearward adjustment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	2%
prevent z rotation so seat doesn't feel cheap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	2%
allow locking of backrest	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	2%
transfer moment load	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2%
allow backrest angle adjustment and locking	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2%
allow front height adjustment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2%
allow main height adjustment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2%
transfer load from seat belt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2%
Sum	2	1	1	4	1	2	1	1	1	1	1	1	2	2	1	1	1	2	1	3	2	2	2	2	2	1	1	1	43	100%
%	5%	2%	2%	9%	2%	5%	2%	2%	2%	2%	2%	2%	5%	5%	2%	2%	2%	5%	2%	7%	5%	5%	5%	5%	5%	2%	2%	2%	100%	

Figure D.1 Functions to Components Matrix

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Requirements x Components	120. Seat	120.1 Headrest assembly	120.2 Seat backrest assembly	120.2.1 Seat backrest cover	120.2.2 Side airbag sub-assembly	120.2.3 Backrest cover	120.2.4 Backrest foam	120.2.5 Side airbag housing	support sub-assembly	120.2.7 Backrest wire frame	120.2.8 Backrest frame	Seat Base	Seat Base Controls Trim Cover	Adjustable Thigh Support Assembly	Seat Base Cover	Seat Base Foam	Seat Pan	Seat Springs	Rear Seat Base Spring Bracket	Seat Base Frame Assembly	Left Slider/Rail Assembly	Right Slider/Rail Assembly	Slider/Rail Adjustment Activation Lever	Seat Base Frame Members	Backrest Angle Adjustment Assembly	Seat Base Angle Adjustment Assembly	Main Height Adjustment Assembly	Seat Belt Mount & Pretensioner	Sum	%
Seat must fit in defined position in vehicle	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Seat must place driver in defined position in vehicle	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Seat must attach to the vehicle	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3	2%
Seat must not distort upon assembly	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5	3%
Allow for grabbing tool handling device	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5	3%
Allow electronic interface to vehicle	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Limit forward seat travel	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	4	2%
Limit rearward seat travel	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	4	2%
Allow for user to adjust forward limit	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	6	4%
Allow for user to adjust rearward limit	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	6	4%
Visible mechanical areas must be covered	1	1	1	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	6	4%
Allow user to adjust seat height within target range	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	5	3%
Allow user to adjust seat angle within target range	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	5	3%
Allow user to adjust seat depth within target range	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	5	3%
Allow user to adjust backrest angle within target range	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	5	3%
Synchronous locking on both sides for forward and rearward adjustment	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Allow user to lock seat height within target range	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Allow user to lock seat angle within target range	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Allow user to lock seat depth within target range	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%

Figure D.2 Requirements to Components Matrix

Requirements x Components	120. Seat	120.1 Headrest assembly	120.2 Seat backrest assembly	120.2.1 Seat backrest cover	120.2.2 Side airbag sub-assembly	120.2.3 Backrest cover	120.2.4 Backrest foam	120.2.5 Side airbag housing	support sub-assembly	120.2.7 Backrest wire frame	120.2.8 Backrest frame	Seat Base	Seat Base Controls Trim Cover	Adjustable Thigh Support Assembly	Seat Base Cover	Seat Base Foam	Seat Pan	Seat Springs	Rear Seat Base Spring Bracket	Seat Base Frame Assembly	Left Slider/Rail Assembly	Right Slider/Rail Assembly	Slider/Rail Adjustment Activation Lever	Seat Base Frame Members	Backrest Angle Adjustment Assembly	Seat Base Angle Adjustment Assembly	Main Height Adjustment Assembly	Seat Belt Mount & Pretensioner	Sum	%
Allow user to lock backrest angle within target range	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3	2%
Allow user to adjust lumbar height and depth	1	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2%
Allow user to adjust height and angle of headrest	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2%
Seat must allow attachment of seat belt	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1%
Seat must allow attachment of pre-tensioner	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1%
Buckle pre-tensioner must allow for replacement	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Buckle pre-tensioner must withstand torsional load	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1%
Seat must enable electrical adjustment	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Electrical adjustment controls must be on the seat	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Seat must enable manual adjustment	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Manual adjustment controls must be on the seat	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1%
Seat must fulfill safety requirements	1	1	1	1	1	1	0	1	0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	12	7%
Protect user from pinching	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3%
Ergonomic operating concept	1	1	1	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	1	1	0	0	1	1	1	0	13	8%
No breakage or splintering	1	1	1	1	1	1	0	1	0	1	0	1	1	0	0	0	1	0	0	1	0	0	0	1	1	0	0	0	14	8%
Must be recyclable	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3%
Must withstand 1000N on all upward facing surfaces	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	4	2%
Seat must have basic springing	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	4	2%
Backrest must have basic springing	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	4	2%
Springs must not bottom out and hit anything	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	4	2%
Biomechanically acceptable restaint and movement of occupant in a crash	1	1	1	1	1	1	0	1	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	1	0	0	0	0	16	10%
Sum	40	8	14	9	5	3	0	3	1	6	3	14	9	2	1	0	3	5	2	4	5	5	4	7	3	4	4	3	167	100%
%	24%	5%	8%	5%	3%	2%	0%	2%	1%	4%	2%	8%	5%	1%	1%	0%	2%	3%	1%	2%	3%	3%	2%	4%	2%	2%	2%	2%	100%	

Figure D.2 Requirements to Components Matrix (Continued)

			Seat belt tension test to simulate crash							Backrest moment test	Static headrest test	Pendulum impact on headrest	Dynamic frontal impact test			Nose to tail impact (GDV) test		Cargo test			20g test	Child seat test	Side crash test		
Component Parameters x Test Measures		**"If the component parameter is changed in the direction indicated to reduce mass, what will be the effect on the test measure?" (+1 = T.M. increases, -1 = T.M. decreases, 0 = no effect or ambiguous effect on T.M.) ø**	**failure of seat belt**	**fracturing or cracking of parts pertinent to strength**	**opening of locking devices**	**adjustment of adjusting devices**	**operation of folding backrests**	**position of anchoring points**	**forward displacement of backrest**	**Yield curve of backrest**	**Yield curve of headrest**	**energy absorption of headrest from all sides**	**fracturing or cracking of load bearing points,**	**indications of failure in the flow of power,**	**no adjustment or failure of adjustment elements,**	**NIC (neck injury) value,**	**HIC (head injury) value**	**Penetration of backrest,**	**retention of cargo,**	**sharp edges,**	**Failure of seat**	**child seat anchoring points**	**Buckling of seat**	**Sum**	**%**
Direction to change Cpt. Param.	**Components**	**Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) þ**	**-1**	**-1**	**-1**	**-1**	**-1**	**0**	**0**	**-1**	**-1**	**1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**1**	**-1**	**-1**	**-1**	**-1**		
-1	Headrest assembly	**volume of foam**	0	0	0	0	0	0	0	0	0	-1	0	0	0	1	1	0	0	0	0	0	0	**1**	1%
-1		**diameter of tube**	0	0	0	0	0	0	0	0	1	1	0	0	0	-1	0	0	0	0	0	0	0	**1**	1%
-1		**number of mounting points**	0	0	0	0	0	0	0	0	1	-1	0	0	0	-1	1	0	0	0	0	0	0	**0**	0%
-1		**length of interface with back frame**	0	0	0	0	0	0	0	0	1	-1	0	0	0	-1	0	0	0	0	0	0	0	**-1**	-1%
-1	Seat Backrest Cover	**thickness**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	**3**	4%
-1		**surface area**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	-1	0	0	0	**1**	1%
0		**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**% of area which is concave**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	**2**	2%
-1	Side Airbag Assembly	**volume**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	Backrest Cover	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**% of backrest covered**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	**3**	4%
-1	Backrest Foam	**volume**	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	**2**	2%
-1		**density**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0		**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1		**hardness**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	Side Airbag Housing	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	Lumbar Support Assembly	**volume of bag**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**size of pump**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	Backrest Wire Frame	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1		**spring rate**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**length of springs**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	0	0	0	**1**	1%
-1		**number of springs**	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	-1	0	0	0	**2**	2%

Figure D.3 Component Parameters to Test Measures Matrix

			Seat belt tension test to simulate crash							Backrest moment test	Static headrest test	Pendulum impact on headrest	Dynamic frontal impact test			Nose to tail impact (GDV) test		Cargo test			20g test	Child seat test	Side crash test		
Component Parameters x Test Measures		**"If the component parameter is changed in the direction indicated to reduce mass, what will be the effect on the test measure?" (+1 = T.M. increases, -1 = T.M. decreases, 0 = no effect or ambiguous effect on T.M.) ø**	**failure of seat belt**	**fracturing or cracking of parts pertinent to strength**	**opening of locking devices**	**adjustment of adjusting devices**	**operation of folding backrests**	**position of anchoring points**	**forward displacement of backrest**	**Yield curve of backrest**	**Yield curve of headrest**	**energy absorption of headrest from all sides**	**fracturing or cracking of load bearing points,**	**indications of failure in the flow of power,**	**no adjustment or failure of adjustment elements,**	**NIC (neck injury) value,**	**HIC (head injury) value**	**Penetration of backrest,**	**retention of cargo,**	**sharp edges,**	**Failure of seat**	**child seat anchoring points**	**Buckling of seat**	**Sum**	**%**
Direction to change Cpt. Param.	**Components**	**Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) Þ**	**-1**	**-1**	**-1**	**-1**	**-1**	**0**	**0**	**-1**	**-1**	**1**	**-1**	**-1**	**-1**	**-1**	**-1**	**-1**	**1**	**-1**	**-1**	**-1**	**-1**		
-1		**cross sectional area of springs**	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	**2**	2%
0	Backrest Frame	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**thickness**	0	1	0	0	0	0	0	1	1	0	1	0	0	-1	0	1	1	1	0	0	1	**7**	8%
-1		**profile**	0	1	0	0	0	0	0	1	1	0	1	0	0	-1	0	1	1	1	0	0	1	**7**	8%
1		**area of holes**	0	1	0	0	0	0	0	1	1	0	1	0	0	-1	0	1	1	1	0	0	1	**7**	8%
0	Seat Base Controls Trim Cover	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**surface area**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	Adjustable Thigh Support Assembly	**volume**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0		**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**length of adjustment**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	Seat Base Cover	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**% of seat base covered**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1	Seat Base Foam	**volume**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**density**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0		**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1		**hardness**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
0	Seat Pan	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**thickness**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**	1%
-1		**profile**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**	1%
1		**area of holes**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**	1%
0	Seat Springs	**material**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
1		**spring rate**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**length of springs**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**number of springs**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%
-1		**cross sectional area of springs**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	0%

Figure D.3 Component Parameters to Test Measures Matrix (Continued)

			Seat belt tension test to simulate crash							Backrest moment test	Static headrest test	Pendulum impact on headrest	Dynamic frontal impact test			Nose to tail impact (GDV) test		Cargo test			20g test	Child seat test	Side crash test		
Component Parameters x Test Measures		"If the component parameter is changed in the direction indicated to reduce mass, what will be the effect on the test measure?" (+1 = T.M. increases, -1 = T.M. decreases, 0 = no effect or ambiguous effect on T.M.) ø	failure of seat belt	fracturing or cracking of parts pertinent to strength	opening of locking devices	adjustment of adjusting devices	operation of folding backrests	position of anchoring points	forward displacement of backrest	Yield curve of backrest	Yield curve of headrest	energy absorption of headrest from all sides	fracturing or cracking of load bearing points,	indications of failure in the flow of power,	no adjustment or failure of adjustment elements,	NIC (neck injury) value,	HIC (head injury) value	Penetration of backrest,	retention of cargo,	sharp edges,	Failure of seat	child seat anchoring points	Buckling of seat	Sum	%
Direction to change Cpt. Param.	Components	Goal of test measure (+1 = more is better, -1 = less is better, 0 = stay on target) þ	-1	-1	-1	-1	-1	0	0	-1	-1	1	-1	-1	-1	-1	-1	-1	1	-1	-1	-1	-1		
0	Rear Seat Base Spring Bracket	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		thickness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		profile	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
1		area of holes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
0	Left Slider/Rail Assembly	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		thickness	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	3	4%
-1		profile	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	3	4%
1		area of holes	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	3	4%
-1		length of rail	0	0	-1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1	0	0	-3	-4%
0	Right Slider/Rail Assembly	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		thickness	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	4	5%
-1		profile	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	4	5%
1		area of holes	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	4	5%
-1		length of rail	0	0	-1	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1	0	0	-3	-4%
0	Slider/Rail Adjustment Activation Lever	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		size	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		length of lever	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
0	Seat Base Frame Members	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		thickness	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	3	4%
-1		profile	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	3	4%
1		area of holes	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	3	4%
0	Backrest Angle Adjustment Assembly	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		size of plate	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	1	0	1	6	7%
-1		size of teeth	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	1	0	1	0	1	6	7%
-1		range of adjustment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
0	Seat Base Angle Adjustment Assembly	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		size	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	3	4%
-1		length of lever	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
0	Main Height Adjustment Assembly	material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		size	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	3	4%
-1		length of lever	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
0	Seat Belt Mount & Pretensioner	explosive type	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		activation length	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		angle of actuation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
-1		size of bracket	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	2%
			0	10	4	2	0	0	0	5	3	0	16	0	4	-3	0	7	11	6	6	0	13	84	100%

Figure D.3 Component Parameters to Test Measures Matrix (Continued)

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