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Integrated decision support for architecture & supplier identification in early complex system design

Yun Ye

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**ÉCOLE CENTRALE DES ARTS
ET MANUFACTURES
« ÉCOLE CENTRALE PARIS »**

THÈSE
présentée par

Yun YE

pour l'obtention du

GRADE DE DOCTEUR

Spécialité : Génie Industriel

Laboratoire d'accueil: Laboratoire de Génie Industriel

SUJET :

**Integrated Decision Support for Architecture & Supplier Identification in Early
Complex System Design**

**Aide à la Décision pour l'Identification d'Architecture et des Fournisseurs en phase
préliminaire de Conception de Système Complexe**

soutenue le : 22 october 2014

devant un jury composé de :

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2014ECAP0052

Abstract

In order to combine the advantage of standardization with those of customization, modular design has been increasingly used by OEMs (Original Equipment Manufacturers) in complex system development. Different from traditional design, modular design advocates entrusting lead suppliers with full responsibility of a module. In this case, suppliers are involved much earlier in design, and start collaborating with OEMs from the conceptual design phase. This characteristic of modular design makes it impossible to define the product concept before choosing suppliers, as is normally done in the traditional way. Instead, the product concepts and supplier possibilities need to be considered simultaneously. However, this unbreakable link between a module and its supplier is rarely considered in design support methods. Most existing methods treat architecture and supplier as two separate issues. In this work, we propose the Architecture & Supplier Identification Tool (ASIT), which considers performance of both suppliers and their modules. The ASIT is capable of generating all possible product/system architectures based on customer requirements with consideration of new technologies and new suppliers. The overall performance of each architecture is estimated using data of existing products and expert knowledge. Appropriate candidates are identified, taking into account their customer requirements satisfaction, overall uncertainty, and environmental impact, to be considered in conceptual design. The utilization of ASIT is illustrated in a powertrain design case study. Comparing the results from different methods shows that ASIT is an interesting decision support tool for OEMs to identify suppliers and architectures regarding their overall performance.

Key words: Complex system, modular design, early conceptual design, architecture and supplier identification, customer requirements satisfaction, uncertainty, environmental impact estimation

Résumé

Afin de combiner les avantages de la normalisation et de la personnalisation, «la conception modulaire» est utilisée de plus en plus par les OEMs (Original Equipment Manufacturers) dans le développement de systèmes complexes. Différente de la conception traditionnelle, la conception modulaire confie l'entière responsabilité d'un module aux fournisseurs principaux. Dans ce cas, les fournisseurs commencent à collaborer avec les OEMs beaucoup plus tôt dans le processus de conception, et participent à la conception des systèmes depuis la phase de la conception conceptuelle. Avec une approche «conception modulaire», il n'est plus possible de définir le concept produit avant le choix de leurs fournisseurs, comme on le fait en conception traditionnelle. Par contre, les concepts produits et leurs fournisseurs doivent être examinés simultanément au début de la conception conceptuelle. Cependant, le lien incassable entre un module et son fournisseur est rarement pris en compte dans les méthodes de support de la conception. La plupart des méthodes existantes traitent le choix d'architecture et le choix de(s) fournisseur(s) comme deux sujets d'aide au choix séparés. Dans notre travail, nous proposons une méthode et un outil appelé «Architecture & Supplier Identification Tool (ASIT)», qui considère conjointement les performances des fournisseurs et celles de leurs modules. L'ASIT est capable de générer toutes les architectures possibles (toutes les combinaisons à modules donnés) en fonction des besoins client, en tenant compte des nouvelles technologies et des nouveaux fournisseurs. La performance globale de chaque architecture tient compte à la fois l'architecture et de ses fournisseurs, elle est estimée à partir de données de produits existants et de connaissances expertes. Les candidats appropriés (binômes architectures/fournisseurs) sont identifiés (en tenant compte de leur degré de satisfaction clients, de l'incertitude globale, et de l'impact environnemental) pour être considéré dans la conception conceptuelle. L'utilisation d'ASIT est illustré par une étude de cas de conception du groupe motopropulseur. La comparaison des résultats à d'autres méthodes montre que l'approche ASIT constitue un outil d'aide à la décision intéressant pour les OEMs, elle permet l'identification simultanée des fournisseurs et des architectures qui garantissent une performance globale.

Mots clés : Système complexe, conception modulaire, conception conceptuelle préliminaire, identification d'architecture et fournisseur, satisfaction des exigences des clients, incertitude, estimation de l'impact environnemental

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List of abbreviations

ASIT	Architecture & Supplier Identification Tool
ASIT-E	Architecture & Supplier Identification Tool with Environmental
OEM	Original Equipment Manufacturer

Acknowledgements

The defense was held one month ago and now I already started working.

Sitting in front of my desk in an unfamiliar city, I am trying to recall the 2.5 years as a PhD student in LGI. It seems to be a long time ago that I walk along the coulée verte to go to the lab, meet with my supervisors Bill and Marija, eat in the canteen with my friends, and of course sit in front of my desk working on the thesis that seems can never be finished.

At the end of my defense when it came to the stage to thank all my jury members I couldn't control my tears, I realized that I'll not be able to work with them or even see them anymore. It is the end of an era, but things that I learned from them will always be with me, no matter where I go, what I do.

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30 Nov 2014

Shanghai, China

Résumé étendu

Contexte

Un système complexe est un système avec de nombreux composants, interconnexions, interactions, et interdépendances qui est difficile à décrire, comprendre, prévoir, gérer, concevoir et/ou changer (Magee & de Weck, 2004). À cause de la complexité inhérente aux systèmes complexes, leur conception n'est presque jamais faite à partir de zéro, mais principalement à partir de systèmes existants.

Aujourd'hui, afin de combiner les avantages de la normalisation et de la personnalisation, de plus en plus de OEMs (Original Equipment Manufacturers) commencent à utiliser «la conception modulaire» pour le développement de systèmes complexes. La conception modulaire décompose un système en plusieurs modules qui sont étroitement couplés (Gershenson, Prasad, & Zhang, 2003). Les interfaces entre les modules dans une structure de système donné sont en général spécifiées et normalisées (Ro, Liker, & Fixson, 2007). Par conséquent, le changement d'un module du système ne nécessite pas de changements dans d'autres parties du système (Hoetker, 2006). Cette caractéristique permet aux OEMs, d'une part de réduire les coûts du fait de la normalisation, d'autre part de changer les modules plus librement selon les exigences du système, ou encore pour bénéficier d'avances technologiques.

L'utilisation de la conception modulaire influence directement la structure des entreprises (Ro et al., 2007). Afin de gérer le time to market et le coût, la conception et la fabrication des modules sont souvent sous-traitées auprès de différents fournisseurs. Ces fournisseurs gèrent et coordonnent eux aussi la conception et l'assemblage des modules à grande échelle à travers les fournisseurs du 2^{ème} niveau. Par rapport aux fournisseurs de systèmes conçus de manière traditionnelle, les fournisseurs principaux lors d'une conception modulaire participent beaucoup plus tôt dans le processus de conception du système (normalement depuis la phase de conception conceptuelle), ils travaillent de façon plus autonome en raison de leur responsabilité entière des modules qui leur sont confiés. Cette structure d'entreprise permet aux OEMs de coopérer avec les nouveaux fournisseurs plus librement en comparaison avec les entreprises utilisant la conception traditionnelle. En raison de l'importance croissante et de l'indépendance des fournisseurs, les OEMs sont plus attentifs à la sélection de leurs fournisseurs, afin d'optimiser le résultat final. Le fait que les fournisseurs participent depuis la phase de conception conceptuelle, il est nécessaire l'évaluer les architectures potentiels et les fournisseurs potentiels dès la phase de conception conceptuelle.

L'utilisation de la conception modulaire change le processus de développement de produits chez les OEMs. Dans le processus de conception traditionnelle, la sélection de concept et la sélection des fournisseurs sont en général séparées et réalisées par différents départements de l'OEM et ce dans différentes phases de conception. La plupart du temps, les concepts du système sont identifiés et sélectionnés par des experts dans le département de recherche et développement, les pièces (composants)

qui vont être sous-traitées sont décidées, puis le département de gestion des fournisseurs commencent à identifier et sélectionner les fournisseurs de chaque pièce (composant). En conception modulaire, les fournisseurs participent dès la phase de conception conceptuelle, ce qui signifie qu'il ya une phase où les fournisseurs potentiels et les concepts potentiels sont explorés simultanément, les fournisseurs qui vont participer dans la conception conceptuelle sont à identifier. Nous appelons cette phase "La phase d'identification de l'architecture et des fournisseurs".

Dans la phase d'identification de l'architecture et des fournisseurs, les OEMs doivent explorer toutes les possibilités d'architectures répondant aux besoins client (en tenant compte des nouvelles technologies et de nouveaux fournisseurs potentiels), en estimant leurs performances. Normalement, la génération d'architectures fournit un grand nombre de possibilités, correspondant à un grand nombre de fournisseurs. Toutefois, il n'est ni possible, ni approprié d'impliquer tous ces fournisseurs en conception. Par conséquent, le nombre de fournisseurs doit être limité et ce au regard de leurs performances. L'objectif principal de la phase d'identification de l'architecture et des fournisseurs est donc d'identifier les fournisseurs et les architectures ayant les meilleures performances, et ceci dans la phase de conception conceptuelle.

Toutefois, du fait de l'absence de méthode systématique et d'outil de soutien pour cette phase, l'identification de l'architecture et des fournisseurs se fait dans la plupart du temps par brainstorming dans les entreprises. En même temps, les OEMs ont tendance à se précipiter dans la phase du choix d'architecture et des fournisseurs sans explorer un certain nombre de possibilités et donc sans en estimer leur performance globale.

Afin de soutenir les OEMs à travers la phase d'identification de l'architecture et des fournisseurs, un outil d'aide à la décision est nécessaire.

Objectif

Ce travail de recherche vise à soutenir les OEMs dans leur phase d'identification de l'architecture et des fournisseurs lors de la conception modulaire de système complexe.

L'objectif principal est donc :

OBJECTIF DE LA RECHERCHE:

Développer une méthode qui soutient les OEMs (donneurs d'ordres) dans l'identification des fournisseurs et des architectures qualifiés qui doivent être considérés dans la phase de conception conceptuelle en conception modulaire.

Vue d'ensemble des travaux de recherche

Etat de l'art

La plupart des méthodes existantes traitent des méthodes de choix d'architecture et de choix de(s) fournisseur(s) comme deux sujets d'aide au choix séparés. C'est pour cela que nous n'avons trouvé que quatre études qui tiennent compte simultanément ces deux aspects. Dans ces quatre études, Chiu & Okudan (2011) et Nepal et al. (2012) ont proposés des méthodes qui aident à la décision de la sélection simultanée des concepts et des fournisseurs. Zhang et al. (2008) and Zhang & Huang (2010) quant à eux, ont proposé des méthodes pour la configuration simultanée de la plateforme produits et de sa chaîne d'approvisionnement. Cependant, toutes ces méthodes nécessitent une grande quantité de données précises, ce qui n'est pas disponible dans la phase d'identification de l'architecture et des fournisseurs.

Question de recherche

Comme le révèle l'état de l'art, il n'existe actuellement aucune méthode d'aide à la décision appropriée pour la phase d'identification de l'architecture et des fournisseurs, un outil de soutien est donc nécessaire.

Basé sur l'objectif de la recherche, nous définissons la question de recherche comme la suit :

QUESTION DE RECHERCHE:

Comment identifier les fournisseurs et les architectures qualifiés qui doivent être considérés dans la phase de conception conceptuelle?

Objectives spécifiés

Afin de structurer les travaux de recherche, nous avons spécifié les objectifs de recherche en deux étapes principales :

OBJECTIF 1: DEVELOPPER LA METHODE DE BASE

Proposer une méthode orientée par les exigences client, qui utilise les données existantes et les connaissances d'experts (stockée à l'aide d'une base de données efficace). Générer toutes les architectures possibles (en tenant compte des nouvelles technologies et de nouveaux fournisseurs), évaluer les performances des architectures possibles (en tenant compte de la satisfaction des exigences, et du niveau d'incertitude de développement de l'architecture, et ce en considérant à la fois l'architecture et ses fournisseurs), puis identifier un nombre limité d'architectures et leurs fournisseurs ayant une performance appropriée.

OBJECTIF 2: DEVELOPPER DES PLUG-INS A LA METHODE

Ajouter l'estimation de l'impact environnemental dans la méthode proposée.

Apports et perspectives

Contribution

La contribution la plus importante de ce travail est la proposition d'un outil support pour la phase d'identification de l'architecture et des fournisseurs en conception modulaire de systèmes complexes, cet outil est un outil d'identification des candidats proposés. Les architectures et les fournisseurs du système sont simultanément considérés en utilisant principalement des données qualitatives.

La méthode proposée ASIT (Architecture & Supplier Identification Tool) a pour objectif d'aider les OEMs à bénéficier d'une réelle flexibilité en conception modulaire permettant d'intégrer de nouvelles technologies et de nouveaux fournisseurs à l'étape de génération de l'architecture. La satisfaction des exigences, l'incertitude globale, ainsi que l'impact environnemental sont envisagés dès le début de la conception.

Selon les différents besoins des OEMs, il est possible d'ajouter des plug-ins dans le ASIT pour estimer les architectures et les fournisseurs de différents points de vue.

Ce travail propose également une structure de base de données pour les OEMs leur permettant de stocker des données existantes et des estimations d'experts de manière plus efficace. Cette structure sert également de guide pour aider les OEMs à reconnaître les types de données nécessaires à l'exploration des possibilités et à l'estimation de la performance globale des architectures dans la phase d'identification de l'architecture et fournisseur.

Limites et perspectives

Comme toutes les méthodes d'estimation destinées à la conception conceptuelle, une limite majeure de ce travail est liée à la collecte des données. Pour générer de nouvelles architecture il faut intégrer de nouvelles

technologies et de nouveaux fournisseurs, ces nouvelles informations sont extrêmement difficiles à traduire en données pertinentes. Par conséquent, bien que le ASIT s'efforce de réduire la quantité de données requises, les OEMs doivent toutefois faire de gros efforts pour construire la base de données et collecter les données pertinentes. La réduction de données exigées par ASIT peut être un sujet de recherche intéressant.

Pour l'estimation de la performance, ce travail prend en compte trois critères: la satisfaction des exigences des clients, l'incertitude globale au long du développement de produit, et l'impact environnemental. Outre que ces trois critères, il y a d'autres facteurs qui sont intéressants à prendre en compte dans la phase d'identification de l'architecture et des fournisseurs, tels que le coût et les délais du développement. Dans les méthodes existantes, l'estimation de ces deux facteurs nécessite en générale une grande quantité de données quantitatives, donc impropres à la phase d'identification de l'architecture et fournisseur. De futurs travaux de recherche pourraient se pencher sur cette difficulté.

En raison de l'absence de base de données efficace dans les OEMs, nous n'avons pas pu appliquer ASIT à un cas industriel. En collaboration avec des OEMs, il sera intéressant de tester le ASIT pour en mesure sa performance.

1

Introduction

1.1 Context

1.1.1 *Modular design for complex systems*

A complex system is a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change (Magee & de Weck, 2004). Due to the inherent complexity of complex systems, their design is almost never done from scratch, but mainly based on redesign of existing products.

The product architecture is “the scheme by which the function of the product is allocated to physical components”(Ulrich, 1995). An architecture can be integral or modular (Muffatto & Roveda, 2002).

Nowadays, in order to combine advantages of standardization and customization, more and more OEMs (Original Equipment Manufacturers) start to use “modular design” for the development of complex systems. The current “modular design” can be traced back to early 1930s, to the modular design of machine tools (Ito, 2008). Since then, modular design has been gradually used in the design of industrial instrument, home appliance, high-rise building, automotive, and so on. The modular design decomposes a system into different modules that are tightly coupled within and loosely connected to the rest of the system (Gershenson et al., 2003). The interfaces shared among modules in a given system architecture are usually specified and standardized (Ro et al., 2007), therefore the objective is that the changes in one module of the system do not require changes in other parts of the system (Hoetker, 2006). This characteristic on one hand helps OEMs to reduce cost because of standardization, on the other hand gives OEMs more flexibility to change modules according to the evolving system requirements, thus profit from the rapid updating of technology.

The use of modular design also influences the structure of companies (Ro et al., 2007). In order to manage time-to-market and cost, the design and manufacturing of modules is usually outsourced to different lead suppliers. These suppliers manage and coordinate the design and assembly of large-scale modules across 2nd-tier suppliers. Compare to suppliers in traditional design methods, the lead suppliers in modular design

are involved much earlier in the design process of the system (normally from conceptual design), and are able to work more independently because of their full responsibility for an entire module. This company structure allows OEMs to cooperate with new suppliers more freely compare to traditional design. Because of the increasing importance and independence of the suppliers, OEMs are paying more attention to suppliers that they are working with, in order to optimize the outcome of the final product.

The fact that suppliers are involved from conceptual design requires considering product architecture possibilities and potential suppliers that will design and manufacture the modules simultaneously in early modular design phase.

1.1.2 The architecture & supplier identification phase in engineering design

The utilization of modular design is changing OEMs’ product development process.

The engineering design process is normally composed of 5 phases (as shown in Figure 1-1) with slightly different steps in each phase according to different authors (Ogot & Okudan-Kremer, 2004). It is noteworthy that the engineering design is usually an iterative process, which is not represented in Figure 1-1.

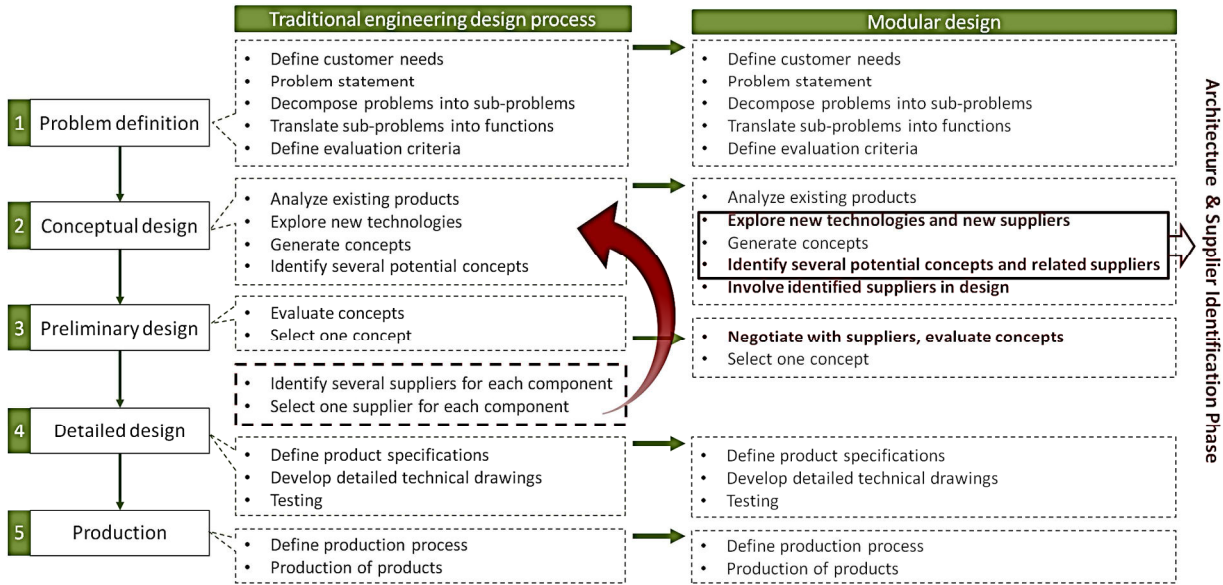


Figure 1-1 Engineering design process

In traditional engineering design (as shown on the left of Figure 1-1), the system concept selection and supplier selection are usually separated and carried out by different departments of the OEM in different design phases. Most of the times, the system concepts are identified and selected by experts in the research and development department, the parts that are going to be outsourced are decided, and then the supplier management department starts to identify and select adequate suppliers for each part.

However, in modular design (as shown on the right of Figure 1-1), suppliers need to be involved from the conceptual design phase, which means that there is a phase where supplier possibilities are explored simultaneously with concept possibilities, and potential suppliers that are going to be involved in conceptual design are identified together with architecture possibilities. We call this phase “the Architecture & Supplier Identification Phase”.

In the “Architecture & Supplier Identification Phase”, OEMs are supposed to explore all architecture possibilities based on customer needs (with consideration of new technologies and new suppliers), and estimate their performances. Normally the architecture generation provides a larger number of possibilities, indicating a long list of suppliers. However, it is neither possible nor appropriate to involve all these suppliers into conceptual design. Therefore, the number of suppliers must be limited and the most suitable ones should be identified. The main goal of the “Architecture & Supplier Identification Phase” is therefore identifying the suppliers and architectures with potentially best overall performance, in order to consider them in conceptual design, and in further negotiation. These suppliers and architectures should form a high quality pool for architecture and supplier selection.

1.1.3 Need of decision support tool for architecture & supplier identification

As presented in the previous section, the OEMs are supposed to explore all possible architectures and identify the best candidates in the Architecture & Supplier Identification Phase.

However, due to the lack of systematic method and supporting tool for this phase, the architecture and supplier identification is still done by brainstorming in most of the companies (Jankovic, Holley, & Yannou, 2012; Moullec, Bouissou, Jankovic, & Bocquet, 2012). At the same time, OEMs tend to rush into the architecture and supplier selection phase without exploring all possibilities and estimating their overall performance.

In order to support OEMs through the architecture and supplier identification phase, a decision support tool is needed.

1.2 Research objective

In order to bridge this gap observed in companies, this work aims at supporting OEMs in the Architecture & Supplier Identification phase in modular complex system design.

The main objective of this work is:

RESEARCH OBJECTIVE:

Develop a method that supports OEMs to identify all qualified suppliers and architecture possibilities that could be involved in the conceptual design phase of modular design.

A list of more developed and specified research objectives is presented in Chapter 2.3.

1.3 Research methodology

This research is carried out by following five main steps: defining research objective, defining research questions, specifying research objectives, proposing solutions, and analysing the influence of the proposed solution, as shown in Figure 1-2.

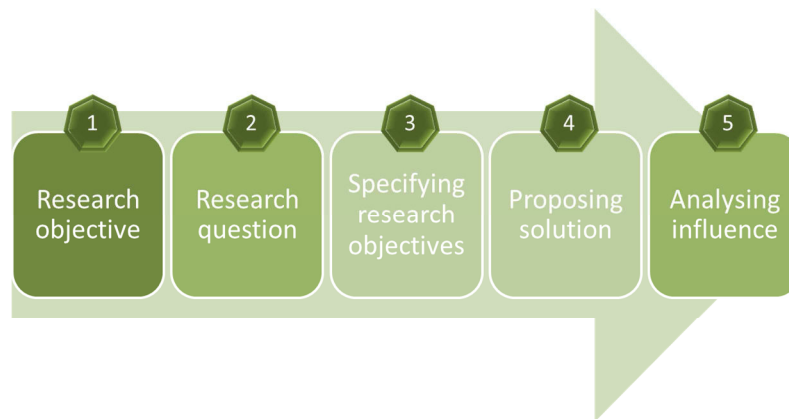


Figure 1-2 Research process

The research objective mainly derives from discussions with people from OEMs such as Airbus, PSA, and Renault. During the discussions, we discovered the need of an architecture and supplier identification support tool within these companies.

By carrying out literature review, we proved the lack of suitable tool for the Architecture & Supplier Identification phase, and defined the research question. The research objective is then further specified in order to lead the solution proposition.

As stated by Eckert, Clarkson, & Stacey(2003):

“Radically different approaches can often only be developed if one steps away from industrial practice to look at the real structure of a problem, and does not engage with the more mundane concern of people in process.”

The method development in this thesis is also done “one step away from industry”. However, it has always been under supervision of people with many years of industrial experience. The utilization of

developed method is illustrated using a simplified industrial case —powertrain design for a plug-in hybrid vehicle.

The validation of the proposed method is done by comparing results with other design supporting methods, and analysing influence of proposed method on architecture and supplier identification results. Nowadays, database used varies from company to company, and information sharing between OEMs and their potential suppliers are of different level. Therefore, it was difficult for us to find all information required by the proposed method in any companies' existing database. Because of this reason, we compared the method to existing tools to observe influence on result it may bring to the architecture and supplier identification.

1.4 Dissertation structure

This doctoral dissertation adopts a recent spring-up format — a format that uses published or submitted scientific articles as main chapters. Utilization of this format requires the PhD candidate and supervisors to have a clear overview of the PhD project since the very beginning, separate the research work into relatively independent parts, and publish each part as scientific paper.

This format makes the research work more organized, the objective of each part more clear, and the contribution of each part validated by publication. However, this format also causes a certain degree of repetition among different articles, for which we ask for kind understanding of readers.

The main contribution of this PhD project is represented by the following three scientific papers published or submitted:

- Ye, Y., Jankovic, M., Kremer, G.E., Bocquet, J.-C., 2014, "Managing Uncertainty in Potential Supplier Identification", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* 28(4)
- Yun YE, Marija JANCOVIC & Gül E. KREMER (2014). Understanding the Impact of Subjective Uncertainty on Architecture Generation and Supplier Identification in Early Complex Systems Design. *Submitted to ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*
- Ye, Y., Jankovic, M., Kremer, G.E., Yannou, B., Leroy, Y., Bocquet, J.-C., 2014, "Integration of Environmental Impact Estimation in System Architecture & Supplier Identification", *submitted to Journal of Mechanical Design*

Relationships between chapters are shown in Figure 1-3.

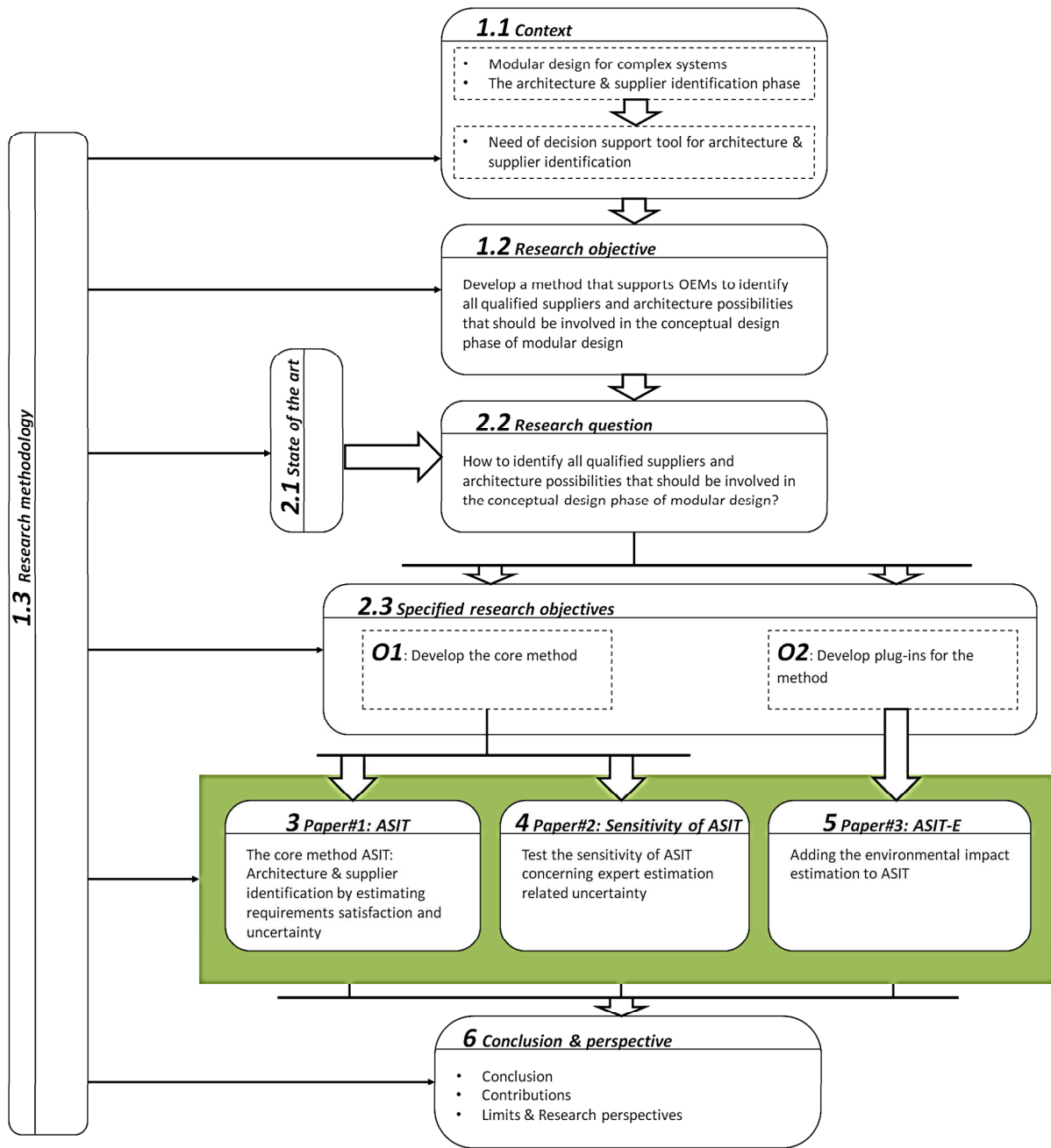


Figure 1-3 Dissertation structure

2

Research overview

2.1 State of the art

In order to respond to the needs of an architecture & supplier identification tool for modular design, we first focused on early design support methods that consider architecture and supplier simultaneously during our literature review.

Since most of the existing methods treat architecture and supplier as two separate issues (Gunasekaran, 1998), we found only four studies that simultaneously consider these two aspects. A more detailed literature review can be found in 3.2.3.

Chiu & Okudan (2011) proposed an interesting integrative methodology that helps to make product design and supply chain decisions simultaneously. This method uses comparatively precise quantitative data such as shape and stiffness of components, and mainly focuses on optimizing overall cost and lead time of the architecture. This method is not suitable for the Architecture & Supplier Identification phase mainly because that the quantitative data required in this method makes it impossible to consider new technologies and new suppliers. However, exploring all possibilities by integrating new technologies and suppliers is one of the most important objectives of the Architecture & Supplier Identification phase. Nepal et al. (2012) also proposed a method that matches product architecture with supply chain design. Same as the previous method, this method also requires precise quantitative data and mainly focuses on cost and lead-time optimization.

Zhang et al. (2008) and Zhang & Huang (2010) proposed methods for simultaneous configuration of platform products and supply chain. The two works used mixed integer linear programming model and game theoretic approach respectively. These two methods require a bigger amount of quantitative data than the previously presented methods during calculation and optimization.

As it can be seen from the literature review, all existing methods that interactively consider product architecture and supply chain issues require large amount of precise quantitative data. However, in the Architecture and Supplier Identification phase, information is usually lacking because of new technology

and supplier integration. Therefore, existing methods are not suitable for the Architecture and Supplier Identification phase.

The literature review that is specific to each research question is presented in detail in Chapters 3 (for design methods that consider simultaneously architectures and suppliers), Chapter 4 (for consideration of subjective uncertainty), and Chapter 5 (for methods that consider environmental impact in early design).

2.2 Research question

As it can be seen from the literature review, there is currently no existing method that can be used in the Architecture & Supplier Identification phase, where precise quantitative data is not available. An innovative supporting tool that is suitable for this phase is needed.

Based on the research objective, we defined the research question as:

RESEARCH QUESTION:

How to identify all qualified suppliers and architecture possibilities that should be involved in conceptual design phase of modular design?

2.3 Specified research objectives

Since this dissertation adopts the article-oriented format, an overall organization of the research is needed at the beginning of the PhD thesis. Therefore, we first specified the research objectives:

SPECIFIED RESEARCH OBJECTIVES:

- Propose a customer requirements oriented method
- Use existing data and expert knowledge
 - Propose a database structure to efficiently organize OEM's existing data and expert knowledge
- Generate all possible architectures (considering new technologies and new suppliers)
- Evaluate the overall performance of architectures
 - The criteria considered during evaluation should depend on the needs of the OEM, but should at least contain requirements satisfaction of an architecture, uncertainty level of architecture development, and lifecycle environmental impact
 - When evaluating the overall performance of an architecture, the architecture itself and its supplier should be both considered
- Identify a limited number of architectures and suppliers with the most appropriate performance, to be considered in conceptual design

The definition of specific research objectives is mainly based on the characteristics of the Architecture & Supplier Identification phase (e.g. new technology and new supplier integration, uncertainty estimation), issues that are attracting increasing attention in the industrial design world (e.g. environmental impact estimation), as well as discussion with OEMs (e.g. the need of an efficient database structure).

However, it is difficult to meet all research objectives at once. Therefore, we regrouped the research objectives into two separate parts, which form the two main stages of our research:

OBJECTIVE 1: DEVELOP THE CORE METHOD

Propose a customer requirements oriented method, which uses existing data and expert knowledge (stored using an efficient database structure). Generate all possible architectures (considering new technologies and new suppliers), evaluate performance of architectures (including requirements satisfaction of an architecture, and uncertainty level of architecture development regarding both architecture and its suppliers), and identify a limited number of architecture and supplier with the most appropriate performance.

OBJECTIVE 2: DEVELOP PLUG-INS FOR THE METHOD

Add the lifecycle environmental impact estimation into the proposed method.

Therefore, the first part of this thesis consists of developing the core method, while the second part aims at adding an “environmental impact estimation” plug-in on top of the core method and demonstrating how to add customized estimation factors.

In the following sections, chapter 3 and 4 belongs to the first stage. The core method (ASIT) is proposed in chapter 3. When estimating the overall development uncertainty, the expert estimation uncertainty is not taken into account in chapter 3. Therefore, in chapter 4, the sensitivity of the proposed method regarding expert estimation uncertainty is studied in order to find out whether it is necessary to consider expert estimation related uncertainty when estimating overall development uncertainty. In chapter 5, the “environmental impact estimation” plug-in is developed and is inserted into ASIT.

3

Paper#1. Managing Uncertainty in Potential Supplier Identification

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Abstract. As a benefit of modularization of complex systems, Original Equipment Manufacturers (OEMs) can choose suppliers in a less constricted way when faced with new or evolving requirements. However, new suppliers usually add uncertainties to the system development. Since suppliers are tightly integrated into the design process in modular design and therefore greatly influence the outcome of OEM's products, the uncertainty along with requirements satisfaction of the suppliers and their modules should be controlled starting from potential supplier identification. In addition, to better satisfy new requirements, the potential supplier identification should be combined with architecture generation to enable the new technology integration. In this paper, we propose the Architecture & Supplier Identification Tool (ASIT), which generates all possible architectures and corresponding suppliers based on new requirements through matrix-mapping and propagation. Using ASIT, the overall uncertainty and requirements satisfaction of generated architectures can be estimated and controlled. The proposed method aims at providing decision support for early design of complex systems, thereby helping OEMs have an integrated view of suppliers and system architectures in requirements satisfaction and overall uncertainty.

Keywords. complex systems design, modularity, potential supplier identification, uncertainty management

3.1 Introduction

In order to reduce complexity and increase manageability of complex systems, one of the principles used in systems engineering is to cluster system elements into larger chunks (Chiriac et al., 2011); this is known as modularization. The design and manufacturing of these modules is often outsourced to different suppliers for reducing or managing time-to-market and cost. Consideration of interfaces (Tripathy & Eppinger, 2011), cost reduction (Nepal et al., 2012), platform policy (Zhang et al., 2008) and new technology integration (Chiu & Okudan, 2011) require integrating suppliers starting in early design stages. Since suppliers are getting more and more tightly integrated into the design process in complex system design (Le Dain et al., 2011), they form, together with the OEM, an extended enterprise (Nguyen Van, 2006), and greatly influence the outcome of OEM's final products.

In modular design, interfaces shared among modules in a given system architecture are usually specified and standardized (Ro et al., 2007), so that changes in one module of the system normally do not require changes in other parts of the system (Hoetker, 2006). This gives OEMs the ability to choose suppliers more freely vis-à-vis the evolving system requirements.

Before choosing suppliers for a new system, OEMs usually first identify a group of potential suppliers, let them submit proposals, and then choose a suitable supplier for each module after negotiation. The focus of this work is about this stage where the group of potential suppliers is identified. Normally, OEMs tend to use those suppliers with which they have a prior history of cooperation, since past interactions usually improve communication between buyer and suppliers (Levinthal & Fichman, 1991; Singh & Mitchell, 1996). This leads to faster, cheaper procurement and more successful system development (Hoetker, 2005). However, existing suppliers may not always satisfy all new requirements of an OEM for the system. In such situations, the OEM has to find new suppliers with suitable new modules and technical capabilities. The integration of new suppliers and modules is facilitated by the modularity of system. However, these new suppliers and modules usually add uncertainty due to various reasons (e.g., supplier's capabilities to cooperate well with the OEM, technological uncertainty of new modules, and the uncertain compatibility between modules).

These uncertainties due to new supplier and module integration may impact decision-making of an OEM on identifying potential suppliers, as attested by several studies. For instance, Janssen et al. (2010) assessed the influence of presenting data with or without the uncertainty information on decision-making; a statistically significant shift in preferences was observed when uncertainty information was presented. In addition, uncertainty integration was also found important in system architecture generation (Marie-Lise et al., 2012), which we think should be considered simultaneously with supplier identification, in order to consider possible new technologies to better satisfy new requirements. However, very few methods considered uncertainty while integrating assessment of supplier capabilities in system architecture generation. With the Architecture & Supplier Identification Tool (ASIT), we respond to the need for controlling overall system uncertainty by combining architecture generation and supplier identification.

In this paper, section 3.2 addresses different concepts of modularity as well as approaches that are specifically designed for supplier selection. Section 3.3 discusses different types of uncertainty, and argues for the need to integrate uncertainty information in early design. The overall ASIT process is presented and discussed. In section 3.4, a case study on powertrain design is used to illustrate ASIT. In order to study if the consideration of uncertainty changes choices made in supplier identification, we also compare ASIT with Concept Selection Method (CSM) by King & Sivaloganathan (1999). CSM is a well-known deterministic approach for concept evaluation that does not consider overall uncertainty. The difference in results of these two approaches is discussed in section 3.5. Finally, we provide a discussion of advantages and limit of the ASIT and present our conclusions in section 3.6 and 3.7, respectively.

3.2 Background

3.2.1 Modularity in complex systems

A complex system is a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change (Magee & de Weck, 2004). Systems and complex systems can be decomposed into different levels of modules, and the number of modules increases as the grain size of modules decreases (Chiriac et al., 2011). An example decomposition of a vehicle system is shown in figure 3-1 (Van Eikema Hommes, 2008). In this context, a module is defined as a chunk that is tightly coupled within and loosely connected to the rest of the system (Gershenson et al., 2003). Normally, different levels of modules are also systems or complex systems themselves. The method proposed in this paper applies for systems and complex systems at any level of their decomposition. For example, the case study illustrates applying the method on a powertrain, which is a complex system, and also a first level module in figure 3-1.

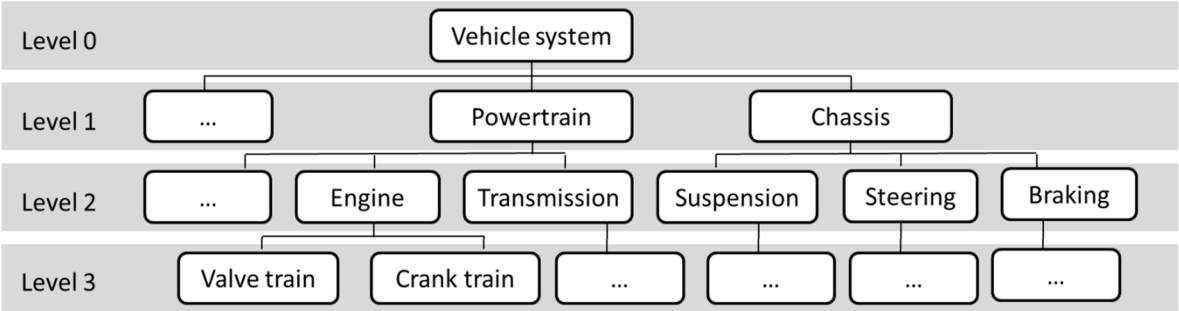


Figure 3-1 Partial decomposition of a vehicle system

3.2.2 Modularity in buyer – supplier relations

According to Fixson & Park (2008), there is a substantial literature stream suggesting that many products are becoming more modular over time. The modularity of products leads to modularity of organizations (Garud et al. 2009). For example, in their empirical work, Ro et al. (2007) found that the emergence of modularity in product design is changing the structure of the extended enterprises in the American auto

industry. The traditional U.S. supplier management model is as shown on the left of figure 3-2. According to Ro et al. (2007), in the traditional supplier management model, the parent department (e.g. chassis department) is further divided into more specialized functional departments (e.g. suspension, steering and braking). Each of the functions is undertaken by an OEM release engineer who manages the first-tier suppliers. In this case, the OEM directly interacts with their suppliers.

The desired form of the U.S. supplier model is called “the systems integrator model” (Ro et al., 2007), which is shown on the right of figure 3-2. In this form, a lead supplier manages and coordinates the design and assembly of large-scale modules and systems across a number of other suppliers. In this case, the OEM needs to communicate only with the integrator suppliers, i.e. the OEM is concerned about the high level modules (e.g., chassis, powertrain, etc.). The integrator suppliers work more independently in this case, and the structure of the extended enterprise is more loose and flexible, implying the formation of a “modular organization”.

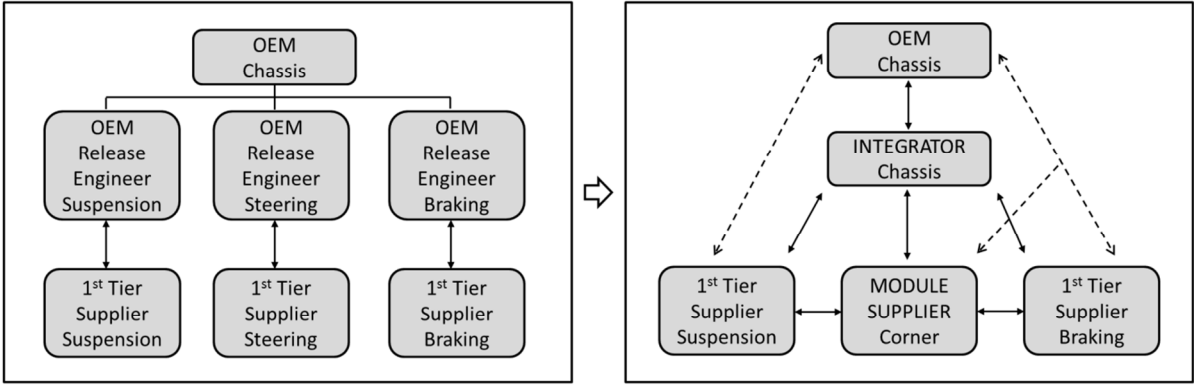


Figure 3-2 Influence of modularity on supplier management model (adopted from (Ro, Liker, &Fixson, 2008))

The ease of reconfiguration of organizational actors in modular organizations allows “modular innovation”, by which firms improve their products by incorporating improvements in various product modules that may occur at different rates for different modules (Langlois & Robertson, 2002). It also allows a firm to select the best supplier for a given module at a given time (Garud & Kumaraswamy, 1995). The proposed supplier identification tool in this paper assumes that the context in which the tool is used reflects the above mentioned buyer-supplier relations and that the tool is proposed as a decision support tool for the said context.

3.2.3 Supplier identification and selection methods

Petersen et al. (2005) demonstrated that “A careful and complete analysis of potential suppliers, leading to the selection of a supplier with the right capabilities and culture to work on the project was positively associated with effective decision making by the project team during the new product development process”. There are hundreds of prior works concerning supplier identification and selection. Most of the supplier selection methods are provided under the traditional product development decision making process, i.e., first the product architecture is fixed by the OEM, then production/manufacturing method is

decided; based on these decisions, suppliers are selected (Nepal et al., 2012). In these methods, product architectures are fixed before supplier selection. The supplier selection is usually based upon financial and managerial criteria such as quality, cost, delivery, and other performances. In early design, however, such data is not necessarily available and is also uncertain. Reviews of supplier selection criteria can be found in works of Ha & Krishnan (2008), Chiu & Okudan (2011) and Ye et al. (2013). The published supplier selection methods under this context are often Multi-Criteria Decision Making (MCDM) methods using mathematical, statistical, artificial intelligence or a combination of these methods. Surveys of these methods can be found in various publications such as by de Boer et al. (2001), Ha & Krishnan (2008) and Chiu & Okudan (2011).

Because of the emergence of modularity, suppliers are more involved in the product design phase. Therefore, companies have started to consider supply chain issues during product development. For example, studies were carried out for matching product development and supply chain design. Ülkü & Schmidt (2011) studied the matching between product modularity level and the supply chain configurations, i.e. the buyer-supplier collaboration level during product design. Pero et al. (2010) studied how new product development and supply chain variables were related to each other; they found that innovation had a strong effect on supply chain complexity and matching product features with supply chains improved performance. Some methods are also provided to address product development and supply chain issues simultaneously. Lamothe et al. (2006) proposed a mixed integer linear programming model to help choose product family variants in a way that the operating cost of the supply chain delivering the product is optimized. More specifically, we have found three studies that consider product design and supplier selection conjointly. Zhang et al. (2008) developed a mixed integer linear programming model to support product platform design. The main objective was to balance the commonality and variety of the product platform. The suppliers were considered simultaneously with the product platform to reduce cost. Chiu & Okudan (2011) proposed a graph theory based method considering product design and supply design simultaneously. In their work, product functions, assembly issues, and supply chain performance were considered in early product design stage. The main objective was to optimize product cost and lead-time. Nepal et al. (2012) proposed a fuzzy logic based framework to tackle product design and supply chain design at the same time. Their objective was to minimize the total supply chain costs, and maximize total supply chain compatibility. The relevant state-of-the-art in concurrent product and supply chain design is summarized by Gan & Grunow (2013).

As can be seen above, among existing studies, Zhang et al. (2008), Chiu & Okudan (2011), and Nepal et al. (2012) addressed product architecture generation and supplier selection simultaneously. All of these consider the cost issue as their main objective. Chiu & Okudan (2011) also considered lead-time, and Nepal et al. (2012) tackled supply chain compatibility issue. However, none of the existing works considered overall uncertainty, which is, in our opinion, an important issue in early design. Because of the frequent high level innovation integration and uncertainty in early complex system design, we address this gap.

3.3 Proposition for Uncertainty Information Integration

3.3.1 Uncertainty sources in supplier identification

De Weck et al. (2007) defined uncertainty as “an amorphous concept that is used to express both the probability that certain assumptions made during design are incorrect as well as the presence of entirely unknown facts that might have a bearing on the future state of a product or system and its success in the marketplace.” Funtowicz & Ravetz (1993) stated that the uncertainty comprises information about the simplifications made during the translation of a natural system into a model.

Many previous works classified uncertainty for early product and system design (Clarkson & Eckert, 2005; McManus & Hastings, 2006; De Weck et al. 2007). The risk management in early design was also investigated by Lough et al. (2009), Van Wie et al. (2005), Altabbakh et al. (2013) and others. In the context of this work, we consider the underlying uncertainty of choosing new suppliers and new modules (possibly using new technologies) during supplier identification.

We identified three sources of uncertainty in using new suppliers and modules: (1) uncertainty related to suppliers' capabilities to cooperate well with the OEM, (2) the probability that a module can be successfully developed, and (3) the compatibility between the modules. For example, supplier A may be able to provide a module B which potentially satisfies the requirements well. However, in reality, the supplier A may not be able to cooperate well with the OEM, and the module B may not be successfully developed. Moreover, even though the module B is developed, it may not be compatible with other modules. In our opinion, these uncertainties should be considered when reviewing the high satisfaction score of supplier A.

3.3.2 Architecture and Supplier Identification Tool

In order to integrate the previously discussed system architecture uncertainties together with supplier capability related uncertainties, we propose the Architecture & Supplier Identification Tool (ASIT). ASIT is a matrix-based method containing information related to requirements, functions, modules, suppliers, and uncertainties. The main objective is to support decision making of the design team in architecture generation and supplier identification. Figure 3-3 presents an overview of the ASIT, which contains four phases that are automated by a MatLab program.

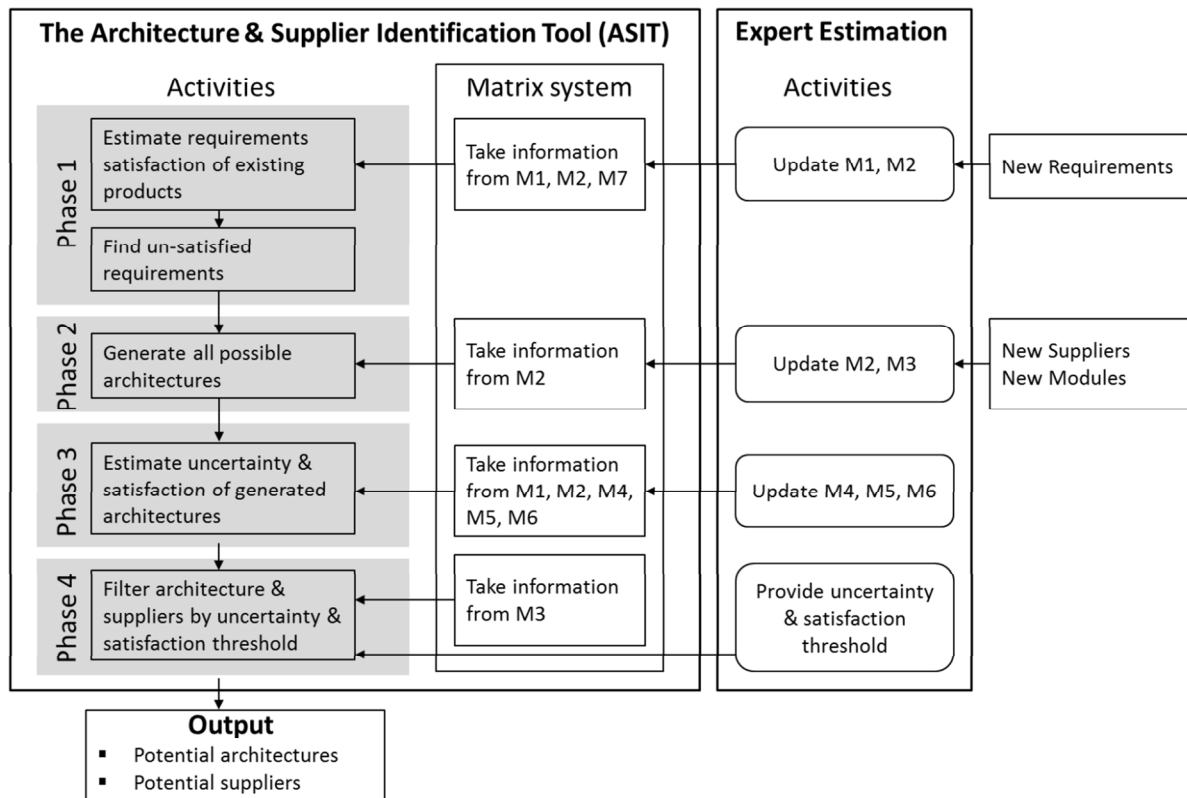


Figure 3-3 Overview of the ASIT

Due to uncertainty management, complex systems are rarely designed from scratch. Therefore, project documents regarding the requirements, functions, and modules usually exist; thus, design information is captured and reused. This information capture and reuse is often facilitated through software (e.g., DOORS). However, various types of data are rarely stored in one place. The idea of ASIT is to store critical, high-level data (pertaining to functions but also requirements, modules, and other types of information) on previous projects within a matrix system. The matrix system is composed of a Design Structure Matrix (DSM) and six Domain Mapping Matrices (DMMs), as shown in figure 3-4.

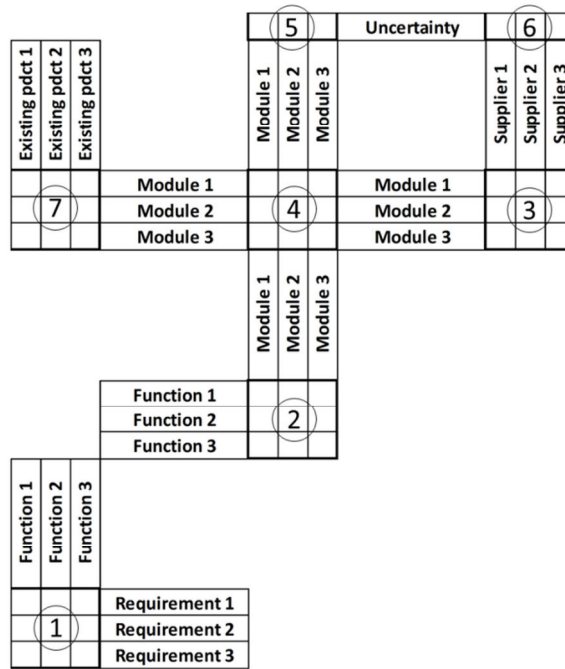


Figure 3-4 The matrix system used in ASIT

When starting a new project, usually the project manager organizes a one to three day workshop to discuss innovation integration, different system architectures, as well as other constraints. These workshops are attended by experts of different domains in order to cover overall system knowledge. With the support of the matrix system in ASIT, the experts can choose the adequate existing requirements from the list, and if necessary add new requirements to it. Based on the requirement-function relations stored in matrix M1, the existing functions related to the defined requirements can be found. Fundamentally, this is a cognitive phase tackling new and existing requirements, where experts will discuss and allocate them to existing functions or create new functions. The functions, in this context, can be seen as translations of requirements to technical language, describing what the module/system should do from a technical point of view. Experts also discuss module types that are needed based on functions, and relations between new functions and module types. Matrices M1 and M2 can be updated after these discussions. The main difficulty in this phase is the expression of requirements and functions due to various semantic possibilities. Here, we assume that designers/engineers are able to define and use a shared language and understanding. Clearly, semantic consistency in reference to functions and other terms is needed.

After the update of matrices M1 and M2, the ASIT can automatically point to (calculate) unsatisfied requirements by existing products using matrices M1, M2 and M7. In phase two, new suppliers and new modules (possibly with new technologies) that can potentially satisfy the unsatisfied requirements are found externally, or proposed by experts, and thereby updating matrices M2 and M3. Then, ASIT automatically generates all possible architectures based on the function – module relations provided in matrix M2. In phase three, uncertainty of generated architectures is calculated based on uncertainty of modules, compatibility between modules, and uncertainty of suppliers’ capabilities. The needed information is provided by a group of experts and stored in matrices M4, M5, and M6. The requirements

satisfaction by generated architectures is also calculated. Finally, in phase four, using the uncertainty threshold and the requirements satisfaction threshold defined by the experts, the generated architectures are filtered to identify potential architectures and corresponding suppliers.

As explained above, information stored in the matrix system comes from two sources: (1) information estimated by experts, and (2) information from existing products. A group of experts work together to provide expert estimation by using predefined levels (as shown in figure 3-5 and 3-6). The information on existing products is considered already stored in the matrix system, as after each project, the related data in the matrix system is updated based on project outcomes. The expert estimation contains four types of information: (1) percentages used in matrix M1, representing the level a function fulfils a requirement, (2) satisfaction levels used in matrix M2, representing how well a module satisfies a function, (3) probabilities as defined in figure 3-6, describing uncertainties in matrices M4, M5, and M6, and (4) binary information, used to define whether one element belongs to another element (matrices M3 and M7).

The satisfaction levels used in ASIT are defined as “interval scales” (Stevens, 1946), so that operations such as addition, subtraction, multiplication by a real number are meaningful. Ten levels (1-10) are used for representing satisfaction, “1” is defined as “very inadequate solution”, and “10” is defined as “ideal solution”. The unit of measurement is 1/10 of the satisfaction difference between “1” and “10”. The descriptive meanings for the satisfaction levels are adapted from Fiod-Neto and Back’s parameter value scores (Fiod-Neto& Back, 1994, pp. 35–45), and are shown in figure 3-5. “0” is used to represent “the module does not provide the function”. During workshops, experts use the linguistic terms in figure 3-5 to provide their estimations, then the linguistic terms are quantified using 1-10 scale equivalents.

Linguistic terms	Satisfaction level
Very inadequate solution	1
Weak solution	2
Tolerable solution	3
Adequate solution	4
Satisfactory solution	5
Good solution with few drawbacks	6
Good solution	7
Very good solution	8
Solution better than requirements	9
Ideal solution	10

Figure 3-5 Linguistic terms for satisfaction levels (Fiod-Neto& Back, 1994)

Probabilities are also often provided using linguistic terms by experts (Meyer & Booker, 2001). Many previous works provided natural language terms associated with probabilities (e.g., Boehm (1989), Conrow (2003), Hamm (1991), Lichtenstein & Robert (1967), and Moore (1983)). However, in these previous works, the proposed probability-related terms were different (Hillson, 2005). Therefore, based on linguistic terms listed in works of Hillson (2005) and Halliwell & Shen (2009), we propose a list of

linguistic terms as shown in figure 3-6. The experts provide their estimations using these linguistic terms for ASIT.

Linguistic terms	Probability
Impossible	0
Nearly impossible	0.1
Very unlikely	0.2
Quite unlikely	0.3
Possible	0.4
Even chance	0.5
Better than even chance	0.6
Quite likely	0.7
Very likely	0.8
Nearly certain	0.9
Certain	1

Figure 3-6 Linguistic terms for probabilities

In the next section, a powertrain design case is used to illustrate the implementation of ASIT.

3.4 Implementation

3.4.1 Case Study Description

We use the powertrain design for a motor vehicle to demonstrate the utilization of ASIT. Due to innovation integration as well as fuzziness in early design (Marie-Lise et al., 2012; De Weck et al., 2007), a vehicle is usually decomposed into two or three levels of subsystems at this stage. The powertrain is one of the high-level subsystems that can be further decomposed. The main objective in designing a powertrain is to provide adequate propulsion with minimal use of fuel while emitting minimal hazardous by-products or pollutants. For the sake of simplicity, only gas engine and hybrid engine architectures are considered for the powertrain in this case study.

A powertrain is a system of mechanical parts in a vehicle that first provides energy, and then converts it in order to propel the vehicle. In a traditional gas-engine vehicle, the engine provides power converted from other sources of energy. The transmission then takes the power, or output, of the engine and, through specific gear ratios, slows it down and transmits it as torque. Through the driveshaft, the engine’s torque is transmitted to the final drive (wheels, continuous track, etc.) of the car. In hybrid electric vehicles, besides the four modules mentioned above, batteries provide electrical energy, and electric motors are used to transform electric energy into torque. Therefore in this study, we consider six types of modules: engine, battery, transmission, electric motor, driveshaft and final drive.

In general, when considering couplings that exist within a powertrain system as well as new architectures that are emerging due to new technologies (e.g., hybrid and electric vehicle), the powertrain can be

considered as a complex system. Michelena & Papalambros (1995) also stated that “in practice, this task is completed incrementally by trial and error and is costly and time consuming.” Further, as a system of variables to be optimized it is overwhelming; Wagner (1993) showed through tested mathematical models that a powertrain system design can have 87 design relations, 127 variables, and 57 degrees of freedom. However, in this case study, not all subsystems and technologies are considered in order to simplify the explanations.

Due to the increasing demand of lower emissions and higher fuel efficiency, the OEM plans to design a new powertrain for their motor vehicle to better satisfy market needs. The new powertrain needs to satisfy 6 requirements (requirements (1) to (5) are adapted from (Michelena & Papalambros, 1995)), including: (1) fleet averaged corporate average fuel economy (CAFE) standard (Violation of this standard results in proportional fines.), (2) acceleration time (This directly relates to customer perceived performance.), (3) Cruising velocity at gradient (Relates to the speed at which vehicle can climb a 6% gradient in forth gear.), (4) The 0-60 mph time (This requirement relates to average speed vehicle acceleration over the speed range of the engine.), (5) Greenhouse gas emissions (This measure shows a vehicle's impact on climate change in terms of the amount of greenhouse gases (e.g., CO₂) it emits.), and (6) Rechargeable by external electric power (This requirement indicates that the OEM would like to develop a plug-in hybrid electric vehicle using rechargeable batteries, the new trend in the market). These requirements can be satisfied by certain functions (e.g., transform energy to torque), and each of the functions is satisfied by one or more modules (Ulrich & Eppinger, 2000). For the new powertrain development, the OEM expects optimum performance of the system, but at the same time, the uncertainty of system development has to be controlled.

3.4.2 Phase I – Requirements satisfaction by existing products

For the new powertrain design, a list of requirements is defined by a group of experts. The aim of this phase is to use ASIT to calculate how the OEM's existing powertrains satisfy these requirements, and which functions are not satisfied, pointing to the need for new module development.

Existing information is stored in the ASIT matrix system. When starting a new project, the matrices M1 and M2 need to be updated by experts with new requirements and functions. Identification of requirements requires experts first to choose appropriate existing requirements, and then add new requirements to the list, if necessary. By using the requirement – function relations in matrix M1, functions that satisfy these requirements are allocated. Experts allocate newly identified requirements to existing functions or add new functions. With new requirements and functions added, the requirement – function relations in matrix M1, and function satisfaction by modules in matrix M2 are estimated by experts. The updated matrix M1 is shown in figure 3-7, where the requirement “rechargeable by external electric power” is a new requirement, and the function “accept recharge” is a new function.

M₁

	Functions						
	Respect environment	Economize fuel	Provide power	Transform energy to torque	Transmit torque to final drive	Interact with surface	Accept recharge
CAFE standard	0	0.5	0.5	0	0	0	0
Acceleration time	0	0	0.6	0.2	0.2	0	0
Cruising velocity at gradient	0	0	0.7	0	0	0.3	0
0-60 mph time	0	0	1	0	0	0	0
Low greenhouse gas emission	1	0	0	0	0	0	0
Rechargeable by external electric power	0	0	0	0	0	0	1

Figure 3-7 M1: Requirement – function relations

The updated matrix M2 is shown in figure 3-8, where a new function is added, and module types needed are also identified by experts.

M₂

	Modules						
	Engine 1	Engine 2	Battery 1	Transmission 1	Electric motor 1	Driveshaft 1	Final drive 1
Respect environment	2	4	8	0	0	0	0
Economize fuel	2	4	10	0	0	0	0
Provide power	8	6	2	0	0	0	0
Transform energy to torque	0	0	0	8	6	0	0
Transmit torque to final drive	0	0	0	0	0	8	0
Interact with surface	0	0	0	0	0	0	8
Accept recharge	0	0	1	0	0	0	0

Figure 3-8 M2: Function satisfaction by modules

After M1 and M2 are updated, ASIT leverages information from M1, M2 and M7 (see figure 3-9) to estimate requirements satisfaction by existing systems. The M7 is an excerpt of the OEM's existing powertrains. In this case study, the OEM successfully developed two types of powertrains in the past (i.e. regular gas engine powertrain and hybrid, as shown in matrix M7 in figure 3-9), which are used as foundations for the new product development. In matrix M7, "1" represents "the module belongs to the architecture", and "0" represents "the module does not belong to the architecture".

M₇

		Gas powertrain	Hybrid powertrain
Modules	Engine 1	1	0
	Engine 2	0	1
	Battery 1	0	1
	Transmission 1	1	1
	Electric motor 1	0	1
	Driveshaft 1	1	1
	Final drive 1	1	1

Figure 3-9 M7: Composition of existing products

In order to propagate the function satisfaction by modules (figure 3-8) to the function satisfaction by architectures, the composition of the existing powertrains (matrix M₇, figure 3-9) is considered. How a system satisfies a function depends on the capability of its relevant modules. When there is only one module in the product that is designed to satisfy a function, the satisfaction level of the function by the product is considered the same as the satisfaction level of the function by the module. When there are multiple modules satisfying the function, the satisfaction level is defined as the average of satisfaction levels of the modules. For example, the gas powertrain has only one module (the engine 1) fulfilling the function “provide power”. Therefore, if the “engine 1” satisfies the “provide power” function at level 8, the gas powertrain should also satisfy this function at level 8, as shown in matrix M_{fun-arch} in figure 3-10. The satisfaction levels here represent “how good a module is with regards to a function” qualitatively. Taking the average of satisfaction levels is a simplification adopted in this work; the weights of modules for satisfying a function can also be considered.

M_{fun-arch}

		Gas powertrain	Hybrid powertrain
Functions	Respect environment	2	6
	Economize fuel	2	7
	Provide power	8	4
	Transform energy to torque	8	7
	Transmit torque to final drive	8	8
	Interact with surface	8	8
	Accept recharge	0	1

Figure 3-10 Function satisfaction level of existing products

In order to propagate the satisfaction of functions to the satisfaction of requirements (by existing products), the requirement – function relations (M1, figure 3-7) are used. Numbers in this matrix represent the percentage that a function satisfies a requirement. The sum of each row of the matrix can be greater or equal to 0 and smaller or equal to 1, since the requirements may be only partly satisfied. For propagating the satisfaction of functions to the satisfaction of requirements, we use the formula:

$$M_{req-arch} = M_1 \times M_{fun-arch}$$

The requirements satisfaction of the existing powertrains is shown in figure 3-11.

M_{req-arch}

		Gas powertrain	Hybrid powertrain
Requirements	CAFE standard	5	5.5
	Acceleration time	8	5.4
	Cruising velocity at gradient	8	5.2
	0-60 mph time	8	4
	Low greenhouse gas emission	2	6
	Rechargeable by external electric power	0	1

Figure 3-11 Requirement satisfaction of existing products

We define that the level 5 represents the “satisfactory solution”, and we further define that a requirement is unsatisfied if its satisfaction level is lower than 5 by at least one architecture. Therefore, the requirements “0-60 mph time”, “low greenhouse gas emission”, and “rechargeable by external electric power” are unsatisfied. Using M1 in figure 3-7, one can see that the requirement “0-60 mph time” is related to the function “provide power”; the requirement “low greenhouse gas emission” is related to the function “respect environment”; and the requirement “rechargeable by external electric power” is related to the function “accept recharge”. Then, by using M2 in figure 3-8, one can see that the satisfaction of these three functions depends on the engine and the battery. Therefore, new engines and batteries that can potentially satisfy these functions need to be identified.

3.4.3 Phase II – Generating solutions

The objective of this phase is to find/propose potential new solutions for unsatisfied functions by experts, and then use ASIT to generate all possible architectures. After searching for new modules provided either by new or existing suppliers, two new engines and two new batteries are found. Both engines are from new suppliers; one of the new batteries is from a new supplier, while the other one is from an existing supplier of the OEM. The matrix system including M2 (function satisfaction by modules), and M3 (suppliers) is updated by using expert estimations on new modules and suppliers.

The updated function satisfaction by modules is shown in M'2 in figure 3-12. It can be seen that the two new engines perform well for functions “respect environment” and “economize fuel”, but not as much for “provide power” in comparison to existing modules. The two new batteries perform well in satisfying “provide power” and “accept recharge” but for other functions they do not show much advantage.

M'2

		Modules										
		Engine 1	Engine 2	Engine 3	Engine 4	Battery 1	Battery 2	Battery 3	Transmission 1	Electric motor 1	Driveshaft 1	Final drive 1
Functions	Respect environment	2	4	5	6	8	8	9	0	0	0	0
	Economize fuel	2	4	5	6	10	10	10	0	0	0	0
	Provide power	8	6	6	5	2	5	8	0	0	0	0
	Transform energy to torque	0	0	0	0	0	0	0	8	6	0	0
	Transmit torque to final drive	0	0	0	0	0	0	0	0	0	8	0
	Interact with surface	0	0	0	0	0	0	0	0	0	0	8
	Accept recharge	0	0	0	0	1	6	8	0	0	0	0

Figure 3-12 M'2: Function satisfaction by modules (with new modules)

As indicated by experts during phase 1 when identifying module types, the powertrain of a plug-in hybrid electric vehicle needs an engine, a battery, a transmission, an electric motor, a driveshaft and a final drive. Therefore, by taking one module from each type of modules mentioned in M'2, all possible architectures are generated (see figure 3-13).

		Possible architecture 1	Possible architecture 2	Possible architecture 3	Possible architecture 4	Possible architecture 5	Possible architecture 6	Possible architecture 7	Possible architecture 8	Possible architecture 9	Possible architecture 10	Possible architecture 11	Possible architecture 12
		Modules	Engine 1	1	0	0	0	1	0	0	0	1	0
Engine 2	0		1	0	0	0	1	0	0	0	1	0	0
Engine 3	0		0	1	0	0	0	1	0	0	0	1	0
Engine 4	0		0	0	1	0	0	0	1	0	0	0	1
Battery 1	1		1	1	1	0	0	0	0	0	0	0	0
Battery 2	0		0	0	0	1	1	1	1	0	0	0	0
Battery 3	0		0	0	0	0	0	0	0	1	1	1	1
Transmission 1	1		1	1	1	1	1	1	1	1	1	1	1
Electric motor 1	1		1	1	1	1	1	1	1	1	1	1	1
Driveshaft 1	1		1	1	1	1	1	1	1	1	1	1	1
Final drive 1	1		1	1	1	1	1	1	1	1	1	1	1

Figure 3-13 Generated possible architectures

3.4.4 Phase III – Evaluating possible architectures

The objective of this phase is to use ASIT to calculate uncertainty and requirements satisfaction of all possible architectures. The calculation of requirements satisfaction is mainly based on M'2, while the

uncertainty information is provided by a group of experts and stored in M4 (compatibility between modules), M5 (uncertainty of each module), and M6 (uncertainty of suppliers' capabilities).

The matrix M4 shows interface compatibilities between modules due to innovation integration. We define that ‘not compatible’ is equal to “0”, “perfectly compatible” is equal to “1”, and a number between “0” and “1” represents the probability that the two modules work well together. Compatibility between modules in existing products is defined as “1”, while other compatibilities are between 0 and 1. M4 is symmetrical, and the elements describing the relations between modules, which satisfy the same function, do not need any interpretation (since they will never be used in the same architecture). The matrix M5 represents the uncertainty of modules. Similar to the definition of compatibility, we define “not mature at all” as “0” and “mature” as “1”, a number between “0” and “1” represents the probability that the module can be developed successfully by the supplier. Similarly, the matrix M6 represents the probability that a supplier and the OEM can work well together. The matrix M3 represents the relations between modules and suppliers, where the number “1” represents that the supplier provides the module.

Since module uncertainty, supplier uncertainty and compatibility between modules can all be considered in probabilistic terms, we define the uncertainty of an architecture as the product of all its modules' uncertainties, its suppliers' uncertainties and the compatibilities between the modules, because of the independence of probabilities. The matrices M3, M4, M5 and M6 are shown in figure 3-14.

M ₅											M ₆										
1.0	1.0	0.6	0.5	1.0	0.8	0.2	1.0	1.0	1.0	1.0	Uncertainty	1.0	0.5	0.8	1.0	0.3	1.0	1.0	1.0	1.0	
Engine 1	Engine 2	Engine 3	Engine 4	Battery 1	Battery 2	Battery 3	Transmission 1	Electric motor 1	driveshaft 1	Final drive 1		Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Supplier 7	Supplier 8	Supplier 9	
				0.2	0.0	0.3	1.0	0.3	1.0	1.0	Engine 1	1	0	0	0	0	0	0	0	0	0
				1.0	0.5	0.2	1.0	1.0	1.0	1.0	Engine 2	1	0	0	0	0	0	0	0	0	0
				0.2	0.8	0.6	0.8	0.6	0.8	0.8	Engine 3	0	1	0	0	0	0	0	0	0	0
				0.2	0.6	0.9	0.8	0.8	0.6	0.8	Engine 4	0	0	1	0	0	0	0	0	0	0
0.2	1.0	0.2	0.2				1.0	1.0	1.0	1.0	Battery 1	0	0	0	1	0	0	0	0	0	0
0.0	0.5	0.8	0.6				0.7	0.8	0.8	0.8	Battery 2	0	0	0	1	0	0	0	0	0	0
0.3	0.2	0.6	0.9				0.9	0.8	0.9	0.8	Battery 3	0	0	0	0	1	0	0	0	0	0
1.0	1.0	0.8	0.8	1.0	0.7	0.9		1.0	1.0	1.0	Transmission 1	0	0	0	0	0	1	0	0	0	0
0.3	1.0	0.6	0.8	1.0	0.8	0.8	1.0		1.0	1.0	Electric motor 1	0	0	0	0	0	0	1	0	0	0
1.0	1.0	0.8	0.6	1.0	0.8	0.9	1.0	1.0		1.0	Driveshaft 1	0	0	0	0	0	0	0	1	0	0
1.0	1.0	0.8	0.8	1.0	0.8	0.8	1.0	1.0	1.0		Final drive 1	0	0	0	0	0	0	0	0	0	1

Figure 3-14 M3, M4, M5& M6: Uncertainty information

Done in a similar way as in calculating the requirements satisfaction by existing products, the requirements satisfaction by possible architectures is calculated using the matrix M² (in figure 3-12) and the matrix M1 (in figure 3-7). In this case, we assume equal importance of the requirements (this assumption can be changed if needed), an overall requirements satisfaction score is obtained for each architecture X by calculating the average of its requirements satisfaction regarding each requirement Y, as shown by the equation:

$$\text{Overall requirements satisfaction of X} = \frac{1}{6} \sum_{Y=1..6} (\text{Satisfaction of Y by X})$$

The obtained uncertainties and satisfaction levels are presented in figure 3-15. Considering the lack of precision in expert estimation, only two decimal numbers are kept for the results. The “uncertainty” represents the overall uncertainty level of an architecture. The bigger the number, the greater the level of confidence we have for the architecture. The “satisfaction” represents the satisfaction level of the requirements by an architecture. The bigger the number, the better the architecture satisfies the requirements.

Architecture	1	2	3	4	5	6	7	8	9	10	11	12
Uncertainty	0.06	1.00	0.02	0.02	0.00	0.14	0.02	0.02	0.00	0.01	0.00	0.00
Satisfaction	4.73	4.52	4.64	4.53	6.72	6.05	6.18	6.07	7.38	7.17	7.29	7.18

Figure 3-15 Uncertainty and requirements satisfaction of all possible architectures

3.4.5 Phase IV – Architecture filtering

The aim of this phase is to use ASIT to filter possible architectures by their uncertainties and the requirement satisfaction levels. The thresholds are provided by experts.

The OEM tends to keep the architectures with the best performance while rejecting highly uncertain architectures in view of the uncertainty related to the project. In this project, the uncertainty threshold is set to 0.02, and the satisfaction threshold is set to 5. Thus, all architectures with uncertainty lower than 0.02 and satisfaction level lower than 5 are rejected. After filtering, 3 out of the 12 generated architectures remain (architectures 6, 7, 8), as shown in figure 3-16, for final consideration.

Architecture	1	2	3	4	5	6	7	8	9	10	11	12
Uncertainty	0.06	1.00	0.02	0.02	0.00	0.14	0.02	0.02	0.00	0.01	0.00	0.00
Satisfaction	4.73	4.52	4.64	4.53	6.72	6.05	6.18	6.07	7.38	7.17	7.29	7.18

Figure 3-16 Uncertainty and satisfaction filtering of possible architectures

The composition of the architectures 6, 7, and 8 can be found in figure 3-13, and the suppliers for the modules are recorded in matrix M3 in figure 3-14. Since the modules “engine 1”, “battery 1” and “battery 3” do not belong to any of the three selected architectures, these three modules are deleted from the initial list. With regard to suppliers, only suppliers that are contributing to selected modules are kept for further consideration. That is why the supplier 5 is not considered further.

Finally, for battery, transmission, electric motor, driveshaft and final drive, only one supplier remains; for the engine, three potential suppliers are identified for further negotiation.

3.5 Comparison

There are several possibilities to compare the ASIT to others, including the method proposed by Bryant et al. (2005), change propagation method proposed by (Clarkson, Simons, & Eckert, 2004), and risk

management in early design proposed by (Lough et al., 2009). However, in order to investigate how consideration of uncertainty changes supplier identification, we choose to compare the ASIT to a similar matrix-based method that does not consider uncertainty. The Concept Selection Method (CSM) proposed by King & Sivaloganathan (1999) is a well-known matrix based approach which ranks different concepts with consideration of function satisfaction. The consideration of function satisfaction is rare in complex system generation approaches, and that is why CSM was chosen for the comparison (see figure 3-17 for the main differences).

The CSM uses two matrices to represent function satisfaction by modules and compatibility between modules, respectively. For each architecture, the summation of function satisfaction and the product of the compatibility score are multiplied, providing an overall score for each architecture. The CSM and the ASIT use different scales for inputs. The CSM requires that “the total score for all modules with respect to each function to equal 1.0”, and the compatibility between two modules is represented using a 0 – 2 scale. In order to allow the comparison, the inputs of the two methods are normalized.

Differences	CSM	ASIT
Objective	Ranking potential architectures	Identifying potential suppliers
Results provided	A ranking of architectures by using satisfaction and compatibility scores	A clustering of architectures and suppliers by using satisfaction and uncertainty threshold
Estimation target	The satisfaction of functions	The satisfaction of requirements
Definition of modules/concepts	One function is satisfied by only one concept and each concept can satisfy only one function	One function can be satisfied by one or more modules, and one module can satisfy several functions
Consideration of uncertainty	No	Yes

Figure 3-17 Main differences between CSM and ASIT

In CSM, overall scores for each architecture are calculated and ranked (see figure 3-18). In ASIT, only the architectures with requirements satisfaction and uncertainty above the thresholds are identified, with a set of suppliers contributing to a given architecture design (figure 3-18).

CSM (Ranking by score)			ASIT (Clustering: satisfaction \geq 5, uncertainty \geq 0.02)			
Ranking	Architecture	Score	Architecture	Satisfaction	Uncertainty	Supplier
1	2	114.90	7	6.18	0.02	2,4,6,7,8,9
2	6	22.90	8	6.07	0.02	3,4,6,7,8,9
3	12	19.78	6	6.05	0.14	1,4,6,7,8,9
4	10	14.03				
5	11	13.10				
6	7	11.42				
7	8	8.62				
8	4	7.23				
9	3	7.17				
10	1	6.75				
11	9	6.20				
12	5	0				

Figure 3-18 Comparing results of CSM and ASIT

One can see on the left side of the table that when compatibility is considered as part of the performance, the architecture 2 receives a very high score. This is because this architecture is an existing architecture, and thus the “compatibility performance” is very high. Therefore, when adding the “function satisfaction performance” and the “compatibility performance” together, this architecture receives a good performance score although the “function satisfaction performance” alone is not good enough. We can also see that on the left side of the table, the architecture 12 is ranked as the third best architecture. However, it is not among the remaining architectures when considering overall uncertainty, since its uncertainty is lower than the set uncertainty threshold (0.02). Further analysis reveals that the module “battery 3” in the architecture 12 is of uncertainty value 0.2, which means that although this module can potentially provide very good performance, its development is estimated to be very uncertain, and the probability that its supplier works well with the OEM is low (0.3). The same situation can be found for other architectures such as architectures 10 and 11. Uncertainty consideration implies that certain potential architectures (5, 9, 10, 11, 12) are eliminated, resulting in the elimination of supplier 5 providing battery 3 used in architectures 9,10,11,12. As explained before, the battery 3 provides very good performance; however, its uncertainty is very low (In this work, we define “uncertainty = 0” as “not certain at all” and “uncertainty = 1” as “perfectly certain”).

3.6 Discussion

We have seen that the consideration of overall uncertainty influences the result of potential supplier identification. This is because the suppliers, which are potentially high performing but also highly uncertain, are excluded based on the risk that the OEM is willing to take on for the project. In financial terms, return is always accompanied by risk. High return options usually also have high risk. That is why return/risk trade-offs are necessary when making financial decisions. Using the corollary in engineering design, the concepts with better performance might also have higher uncertainty. Therefore, we propose

to consider both performance and uncertainty when making decisions in architecture generation and potential supplier identification. In addition, we have also seen that when considering performance and uncertainty, the two should be considered separately to prevent mixing up the two different indicators.

As proposed in this work, ASIT can assist OEMs in considering performance and uncertainty when identifying suppliers. The use of matrices as a database form in ASIT provides two main advantages when using this tool in early design of complex systems. Firstly, the usage of matrices is practical since the number of modules is limited, as only the first tier suppliers are considered. The explicit form of matrices makes the relations between elements clear, facilitating comprehension and communication between experts. In addition, the storage of two dimension matrices does not require special techniques. This flexibility enables companies to continue using tools that they are familiar with. Standardization in terms of the vocabulary used while describing requirements, functions, etc. also ensures consistency. The matrices used in ASIT are organized as a matrix system. There are prior works that also use matrix systems, such as the Quality Function Deployment (QFD) (Rosenthal, 1992), the concept selection method (King & Sivaloganathan, 1999), the architecture generation method (Bryant et al., 2005), and the multiple-domain design scorecard method (Jankovic et al., 2012). With the mapping flow of requirement – function – module – supplier – uncertainty, ASIT is the first tool to incorporate supplier and uncertainty information, which allows integrating uncertainty information when considering architecture and supplier simultaneously, and features a “variable” view of the design (i.e., design is not fixed).

However, there are several limitations in this work. Firstly, as an initial step towards introducing uncertainty to supplier identification combined with architecture generation, the sources of uncertainty considered in this work may not be exhaustive. Although the information used is mostly from expert estimation, we have not considered the subjectivity in expert estimation. The sensitivity of ASIT regarding this type of uncertainty should be investigated in future works to verify the robustness of this tool. Secondly, with specific regards to performance, only requirements satisfaction is considered in this paper. Many other types of performance are also important in the supplier identification (e.g., sustainability, product cost and lead-time, etc). We believe that the feasibility of getting this type of information in early complex system design stage needs to be considered. Thirdly, the weights of requirements, and the importance of modules for satisfying a function (when the function is satisfied by more than one module) are considered to be equal in this paper. It might be fruitful to explore using varying weights. Moreover, several studies pointed out the need for investigating the impact of preference aggregation and collaborative expert estimation. We believe that this is an important issue and it should be tested within an industrial setting. The work of Clemen & Winkler (1999) and Keeney (2009) set a good basis for future research in this aspect. Regarding the validation of the proposed tool, it will be necessary to test the tool in an industrial environment in the future.

3.7 Conclusions

Potential supplier identification is the phase of preparing supplier candidates for supplier selection by the OEMs. Because of the use of modular design in complex systems, the suppliers are more and more

involved in system design, which makes the technical ability of suppliers more important to better satisfy system requirements. However, using novel architectures and suppliers with potentially better performance often comes with higher uncertainty as well.

In this paper, we proposed ASIT (Architecture & Supplier Identification Tool), which uses both requirement satisfaction and uncertainty thresholds to filter possible architectures and suppliers. The uncertainty related to suppliers' capabilities to cooperate well with the OEM, the technological uncertainty in new modules, and the uncertainty of compatibility between modules are considered. To the best of our knowledge, ASIT is the first supplier identification tool that combines architecture generation where the overall uncertainty is controlled. By comparing to a method, which does not consider uncertainty using a case study of powertrain design, it is shown that considering uncertainty impacts the result of the supplier identification, and that uncertainty should be considered independently from the performance.

Suppliers with potentially high performance may also have high uncertainty. The utilization of ASIT in supplier identification has the potential in balancing risk and return for the OEM while identifying optimal suppliers.

3.8 Reference

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4

Paper #2. Understanding the Impact of Subjective Uncertainty on Architecture Generation and Supplier Identification in Early Complex Systems Design

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Abstract. *The Architecture & Supplier Identification Tool (ASIT) is a design support tool, which enables identification of the most suitable architectures and suppliers in early stages of complex systems design, with consideration of overall requirements satisfaction and uncertainty. During uncertainty estimation, several types of uncertainties that are essential in early design (i.e., uncertainty of modules due to new technology integration, compatibility between modules, and supplier performance uncertainty) have been considered in ASIT. However, it still remains unclear whether expert estimation uncertainties should be taken into account. From one perspective, expert estimation uncertainties may significantly influence the overall uncertainty since early complex systems design greatly depends on expert estimation; but from another perspective, it is also possible that expert estimation uncertainties should be neglected because it is much smaller in scale comparing to other types of uncertainties in this stage. In order to understand how expert estimation uncertainties (especially subjective uncertainty) influence the architecture and supplier identification results achieved using ASIT, a comprehensive study of possible modelling approaches has been discussed; and the type-1 fuzzy sets and the 2-tuple fuzzy linguistic representation are selected to integrate these subjective uncertainties in ASIT. A powertrain design case is used to compare results when considering subjective uncertainties versus not considering them. Finally, the consideration of subjective uncertainty in early conceptual design and other design stages is discussed.*

Keywords: *expert estimation uncertainty, subjective uncertainty, early conceptual design stage, early complex systems design, fuzzy set theory, 2-tuple fuzzy linguistic representation*

4.1 Introduction

In early design phases of complex systems, the OEMs (Original Equipment Manufacturers) strive to explore possibilities, delay decisions, and at the same time control both the performance and the uncertainty of the future system (Ye, Jankovic, Kremer, & Bocquet, 2014). Nowadays, more and more OEMs tend to involve their suppliers early in design in the context of an extended enterprise (Nguyen Van, 2006), especially in airplane and automotive industries. For example, Airbus has several thousand suppliers from more than 100 countries (Airbus Group, 2014). Among these suppliers, some are called first-tier suppliers, such as Snecma and Roll Royce for engines. These first-tier suppliers usually have the full responsibility of an entire module, and are involved since early conceptual design phase of the system in most of the times. Therefore, it is important to consider the performance and uncertainty of these suppliers when estimating performance and uncertainty of the future system. However, very few methods consider both system architecture design as well as supplier information (Ye et al., 2014). In order to fill this gap, we proposed an Architecture & Supplier Identification Tool (ASIT) (Ye et al., 2014) to support design teams when considering these issues. Given the lack of data, fuzziness and different uncertainties inherent to early design, ASIT takes into account uncertainties related to interfaces, suppliers' capability, and the capability of one subsystem/module to reach a certain performance. These data are estimated by experts using predefined linguistic terms (as shown in Tab.4-1 and Tab.4-2), and these linguistic terms are then translated to related numerical scales to facilitate calculation.

We have observed that when using information comes from expert estimation, many researchers tend to use methods such as fuzzy sets (e.g. J. (Ray) Wang, 2001), rough sets (e.g. Zhai, Khoo, & Zhong, 2009), etc. to model the information in order to represent the expert estimation uncertainties. Because of the integration of new technologies, new modules and new suppliers, ASIT also greatly relies on expert estimation. However, different from most of the existing design supporting methods, ASIT works in the design phase called "early conceptual design stage", where overall uncertainty level is much greater than in later design stages. Therefore, it is unclear whether using mathematical methods to model expert estimation will influence the overall results.

In this paper, we propose to analyse the influence of considering expert estimation uncertainties on ASIT result by answering the following two research questions:

1. Which uncertainty modeling method is most suitable for representing the expert estimation uncertainties within the context of ASIT?
2. How does the consideration of expert estimation uncertainties influence the results of ASIT?

In the following sections, we start by giving an overview of the ASIT, and the uncertainties caused by expert estimation in ASIT. In section three, we give a review of different uncertainty representation methods that can be used to represent subjective uncertainty. The suitability of the uncertainty representation methods is analysed based on the characteristics of the early design stage and the ASIT, making up the set of comparison criteria. In section four, the operations of fuzzy sets, the selection of suitable membership functions, and the utilization of defuzzification methods are discussed. In section

five, the selected representation methods are integrated into ASIT by using a powertrain case study. In section six, the results are compared and discussed before conclusions are presented in section seven.

4.2 The Expert Estimation Uncertainty in ASIT

The ASIT is an early design support tool that aims at generating possible system architectures with the list of suppliers that are co-designing the system. First, possible architectures are generated by integrating new technologies in order to better satisfy new requirements. Then, the generated architectures are filtered by uncertainty and requirement satisfaction thresholds in order to identify the architectures with relatively high performance and low uncertainty. Three major types of uncertainties had been taken into account: (1) uncertainties related to capability of one subsystem/module to reach defined system performances, (2) interface related uncertainties, and (3) uncertainty related to supplier capabilities.

The ASIT contains four phases, as shown in Fig.4-1. In phase one, the satisfaction of new requirements by OEM's existing products is calculated by using data of existing products stored in database. Subsequently, the un-satisfied requirements, un-satisfied functions, and responsible modules types for the un-satisfaction are found through mapping of "requirement – function – module type". In phase two, new solutions for the responsible module types are found by experts in existing or new supplier companies. Then, all possible architectures are generated by taking one module from each module type. In phase three, uncertainty of generated architectures is calculated based on experts' estimation of the three types of uncertainties; the requirements satisfaction level of architectures is calculated based on experts' estimation about "function satisfaction by modules". Finally, in phase four, by using the uncertainty and requirements satisfaction thresholds (which are defined by the OEM based on the tolerance of requirements satisfaction, and the risk that they are willing to take), the generated architectures are filtered to identify potential architectures and corresponding suppliers.

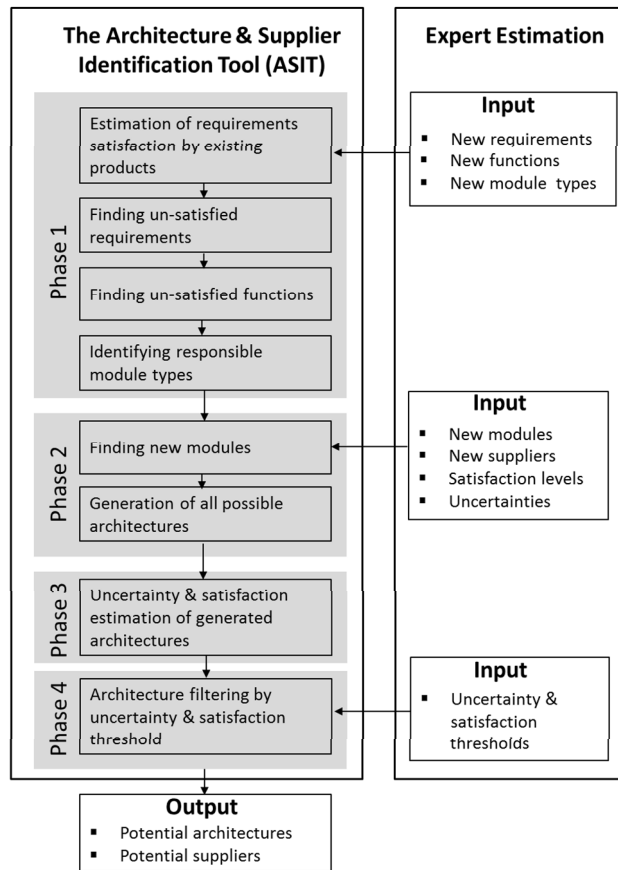


Figure 4-1 Overview of ASIT

During the process of ASIT, experts are mainly solicited for two types of information: satisfaction levels, and uncertainties. Although expert evaluations are often expressed in an informal way, there are many methods to make them more precise. The mostly used method is the pre-defined linguistic terms or ordinal scales. In ASIT, the satisfaction levels (Fiod-Neto & Back, 1994) and uncertainties are predefined as shown in Tab.4-1 and Tab.4-2. Here, the two forms (i.e., linguistic and numerical) are provided together since the linguistic terms provide explanatory notes while the numerical levels facilitate aggregation

Table 4-1 Satisfaction levels

Linguistic terms	Satisfaction level
Very inadequate solution	1
Weak solution	2
Tolerable solution	3
Adequate solution	4
Satisfactory solution	5
Good solution with few drawbacks	6
Good solution	7
Very good solution	8
Solution better than requirements	9
Ideal solution	10

Table 4-2 Probabilities

Linguistic terms	Probability
Impossible	0
Nearly impossible	0.1
Very unlikely	0.2
Quite unlikely	0.3
Possible	0.4
Even chance	0.5
Better than even chance	0.6
Quite likely	0.7
Very likely	0.8
Nearly certain	0.9
Certain	1

Expert knowledge is seen by Meyer and Booker (2001) as “what is known by qualified individuals, responding to complex, difficult (technical) questions, obtained through formal expert elicitation”.

As human beings, experts generate two categories of uncertainty: aleatory (random) and epistemic (subjective) (Medsker, Tan, & Turban, 1995). The aleatory uncertainty is also referred to as inherent uncertainty, irreducible uncertainty, and variability. It describes uncertainty due to random variation or inherent variation (Booker, Anderson, & Meyer, 2003). This type of uncertainty is considered rooted in the way that the brain processes information (Dror & Charlton, 2006). The epistemic uncertainty is also referred to as subjective uncertainty and reducible uncertainty. The fundamental cause of this type of uncertainty is incomplete information or incomplete knowledge of some characteristic of the system or the environment (Oberkampf, Helton, & Sentz, 2001). Aleatory and epistemic uncertainties both exist in expert estimation. However, in early conceptual design phase of complex systems, very limited amount of information is available, which causes high level of epistemic uncertainty. In comparison to the epistemic uncertainty, the aleatory uncertainty, in this phase, is much smaller in scale. Therefore when integrating the two types of uncertainties, the aleatory uncertainty can be covered by the epistemic uncertainty. That is why we propose to consider only the epistemic uncertainty in the context of this study.

One of the strategies to reduce epistemic uncertainty in complex system design is to use expert group evaluations (Medsker et al., 1995). In this study, we assume that a group of experts is used for each estimation, in order to prevent the situation that one expert does not have enough knowledge in a specific domain.

According to the discussion above, one can see that the most important uncertainty caused by expert estimation in ASIT is the subjective (epistemic) uncertainty, which is caused by the lack of information in early design. In order to test the sensitivity of the ASIT to this type of uncertainty, we need to first choose a suitable uncertainty representation method to model this type of uncertainty. In the next section, several approaches that can model the subjective uncertainty are investigated and discussed according to the characteristics of the early design stage, the ASIT, and subjective uncertainties within ASIT.

4.3 Representing Subjective Uncertainty in ASIT

In order to identify the most suitable method for representing subjective uncertainty in ASIT, we have compiled uncertainty representation methods that have been the most commonly used for representing this type of uncertainty (NG & Abramson, 1990; Oberkampf et al., 2001; Booker et al., 2003):

- Subjective probability theory,
- Imprecise probability theory,
- Evidence (Dempster-Shafer) theory,
- Fuzzy sets,
- Possibility theory ,
- Interval analysis theory, and
- Rough sets.

Epistemic uncertainty has been traditionally modelled as probability distributions. The probability theory has four perspectives including classical, empirical, subjective and axiomatic probabilities (Asadoorian & Kantarelis, 2005). The expert estimation can be modelled as subjective probability, which represents an individual's measure of belief that an event will occur. The information gathered for the distribution could be a mixture of limited experimental data and a person's experience, or the elicitation of multiple expert opinions (Oberkampf et al., 2001). The main concern of this method is that the "fuzziness" of information is usually lost since in probability theory, an event either occurs or not (NG & Abramson, 1990).

The imprecise probability (Walley, 1991) is a generalization of probability theory; it is used when a unique probability distribution is hard to identify. In imprecise probability, a lower probability and an upper probability are used instead of one single probability. For an uncertain event A , instead of assigning a single probability $P(A)$, the imprecise probability assigns an interval $[\underline{P}(A), \bar{P}(A)]$ with $0 \leq \underline{P}(A) \leq \bar{P}(A) \leq 1$, where $\underline{P}(A)$ is the lower probability for A , $\bar{P}(A)$ is the upper probability for A , and $\Delta A = \bar{P}(A) - \underline{P}(A)$ is the imprecision for event A (Coolen, 2004). Similar to the probability theory, the fuzziness of information is thought to be lost when using imprecise probability.

The evidence (Dempster-Shafer) theory (Dempster, 1967; Shafer, 1976) is a generalization of the Bayesian theory of subjective probability. It allows considering the confidence one has in the probabilities assigned to the outcomes. The evidence theory uses an interval to represent the probabilities with a lower bound called "believe" and an upper bound called "plausibility". The "believe" is the sum of the evidence that supports the hypothesis, while the "plausibility" is 1 minus the sum of the evidence that opposes the

hypothesis. According to NG & Abramson (1990), one obvious problem of the evidence theory is its implementation complexity since experts must provide all the beliefs for all subsets of possible hypotheses.

In 1965, Zadeh (1965) started a revolution in uncertainty thinking by introducing the fuzzy set theory. This theory uses a membership function to represent the degree of membership of an element to a set of objects. The degree to which an element belongs to a set is defined by a value between 0 and 1; the higher the value is the greater its belongingness, and an element can partly belong to a fuzzy set. The fuzzy set is widely used in describing linguistic information since it can effectively represent the gradual changes of people's perception of a concept in a certain context (Dalalah & Magableh, 2008). Moreover, the fuzzy set theory also allows mathematical operations that help to provide quantitative methods to deal with qualitative data.

The possibility theory (Zadeh, 1999; Dubois & Prade, 1988; Cooman, Ruan, & Kerre, 1995) is an extension of the theory of fuzzy sets. It can be used to express the vague terms used by human experts with precision and accuracy (NG & Abramson, 1990).

Interval analysis (Moore, 1979; Kearfott & Kreinovich, 1996) is an approach that treats an interval as a new kind of number (Moore, 1979) and follows the following elementary properties (R. Moore & Lodwick, 2003):

$$[a,b]+[c,d]=[a+c,b+d] \quad (1)$$

$$[a,b]-[c,d]=[a-d,b-c] \quad (2)$$

$$[a,b][c,d]=[min(ac,ad,bc,bd),max(ac,ad,bc,bd)] \quad (3)$$

$$[a,b] \div [c,d]=[a,b][1/d,1/c] \text{ where } 0 \notin [c,d] \quad (4)$$

The rough sets theory (Pawlak, 1982) uses a pair of sets to give the lower and upper approximation of the original set. This theory is used when objects are characterized by the same information and thus are indistinguishable (Pawlak, 1997). Each rough set has boundary-line elements, which cannot be properly classified by using the available knowledge.

These methods have all been used in previous works to represent expert's subjective uncertainty. However, it is not clear how to choose a method according to a specific context (e.g., for ASIT). In order to identify approaches that can be seen as most suitable in the context of ASIT, we propose to consider the following four criteria:

1. **The method is able to represent numerical levels:** In ASIT, experts use predefined linguistic terms and related numerical levels to represent their estimation. Therefore, the chosen method should be able to represent these types of dis-continuous numerical levels.

2. **The method requires reasonable amount of information:** In ASIT, the estimation is provided by experts. Due to the limitations in time, budget and human capacity, the amount of information required by the mathematical representation has to be reasonable.

3. **The method should capture the “fuzziness” of expert estimation:** Human knowledge is imprecise. The chosen method should be able to capture this kind of imprecision.

4. **Support multi-criteria group decision making:** The aim of the potential supplier identification is to provide candidates for the supplier selection, which is usually a multi-criteria group decision making problem. In order to be able to use the supplier identification results directly in the supplier selection stage, the selected uncertainty representation method should be able to combine with other methods to support the multi-criteria group decision making.

With regard to the first criterion (representing the numerical levels), the rough set theory is not suitable since it assumes that some of the elements are characterized by the same information hence indistinguishable. However, the elements defined by the numerical levels are clearly distinguishable (e.g., numbers 1 – 10 used in Tab.4-1).

In view of the second criterion (requiring reasonable amount of information), the evidence theory is inappropriate. According to the principles of evidence theory, experts need to provide $2x$ beliefs for each estimation, where x represents the number of elements. For example, when using satisfaction levels provided in Tab.4-1, x is equal to 10. Therefore, when estimating “how well module A satisfies function B”, experts need to provide 210 beliefs. With the increase of module and function counts, the number of estimation needed increases accordingly.

The third criterion (capturing the “fuzziness” of expert estimation) makes the subjective probability theory, the imprecise probability theory, the possibility theory and the interval analysis theory inappropriate since they are not designed to capture the “fuzziness”.

With regards to the fourth criterion (support multi-criteria group decision making), many fuzzy set based multi-criteria group decision making methods exist, including:

- Fuzzy set theory + TOPSIS (Chen, Lin, & Huang, 2006),
- Intuitionistic fuzzy sets + TOPSIS (Boran, Genç, Kurt, & Akay, 2009),
- Fuzzy AHP (Kahraman, Cebeci, & Ulukan, 2003; Haq & Kannan, 2006; Chan, Kumar, Tiwari, Lau, & Choy, 2008),
- Fuzzy AHP + cluster analysis (Bottani & Rizzi, 2008),
- Fuzzy ANP (Vinodh, Anesh Ramiya, & Gautham, 2011),
- Fuzzy ANP + TOPSIS (Önüt, Kara, & Işık, 2009),

- Fuzzy multi-objective programming (Amid, Ghodsypour, & O'Brien, 2006),
- Fuzzy arithmetic operation (Bayrak, Çelebi, & Taşkin, 2007),
- Fuzzy SMART (Chou & Chang, 2008),
- Fuzzy QFD (Bevilacqua, Ciarapica, & Giacchetta, 2006),
- Fuzzy DEMATEL + TOPSIS (Dalalah, Hayajneh, & Batiha, 2011).

With regard to previously discussed criteria, the fuzzy set theory appears to be the most suitable mathematical representation to express subjectivity in expert estimations. In recent years, several branches of fuzzy set theory were developed; the most popular ones among these with applications in supplier identification and selection are:

- Type-1 fuzzy sets (e.g., Önüt et al., 2009),
- Interval type-2 fuzzy sets (e.g., Chen & Lee, 2010),
- Intuitionistic fuzzy sets (e.g., Boran et al., 2009),
- 2-tuple fuzzy linguistic representation (e.g., Wang, 2010).

The type-1 fuzzy sets is the same as the ordinary fuzzy set theory. The re-name is for the purpose of distinguishing from the type-2 fuzzy sets. This theory uses a membership function to represent the degree of membership of an element to a set of objects. The degree to which an element belongs to a set is defined by a value between 0 and 1. Higher the value is the greater its belongingness and an element can partly belong to a fuzzy set. The fuzzy set is widely used in describing linguistic information since it can effectively represent the gradual changes of people's perception of a concept in a certain context (Dalalah & Magableh, 2008). It is also widely used for representing human uncertainty.

The interval type-2 fuzzy sets is a simplified form of type-2 fuzzy sets, which is defined by Mendel and John (2002) based on Zadeh's Extension Principle (Zadeh, 1975). The type-2 fuzzy sets is able to model one additional degree of uncertainty than the type-1 fuzzy sets. In type-1 fuzzy sets the membership functions are crisp, but in type-2 fuzzy sets the membership functions are themselves fuzzy. Therefore, a type-2 membership function is a three-dimensional membership function, which is sometimes difficult to understand and define. The interval type-2 fuzzy sets simplified the fuzziness of the primary membership function of type-2 fuzzy sets by assuming that the fuzziness of the primary membership function is equal to one. Therefore, the interval type-2 fuzzy sets can be seen as composed of an upper membership function and a lower membership function, which are both of type-1 membership functions. The main problem with using this representation for representing expert estimation is that it might be already difficult for experts to define one membership function; defining two is even harder. Moreover, in the context of representing expert estimation, the definition of the second membership function does not

provide further understanding of the problem. Consequently, the interval type-2 fuzzy sets does not seem to be an effective way to represent subjective uncertainty in expert estimation.

The intuitionistic fuzzy sets was proposed by Atanassov (1986) twenty years after Zadeh's fuzzy sets. The intuitionistic fuzzy sets use dual membership degrees in each of the sets by giving both a degree of membership and a degree of non-membership. Similar to the interval type-2 fuzzy sets, it might be difficult for experts to define two membership functions for each estimation; thus, the intuitionistic fuzzy sets do not seem convenient for representing subjective uncertainty in expert estimation either.

The 2-tuple fuzzy linguistic representation is developed by Herrera & Martinez (2000) based on the fuzzy set theory and the symbolic method (Delgado, Verdegay, & Vila, 1993). The linguistic values (e.g., expert estimation) are usually modelled as fuzzy sets. When aggregating the linguistic values (fuzzy sets), the result usually does not exactly match any of the initial linguistic terms, and thus an approximate linguistic term must be found. However, the imprecision of this approximation is lost. In the 2-tuple fuzzy linguistic representation, the linguistic information is expressed by a 2-tuple (s, α) , where s represents the approximate linguistic term, and α represents the imprecision of this approximation. This representation can efficiently prevent the loss of information and thus help the ranking of alternatives.

Given the discussion above, we think that the type-1 fuzzy sets and the 2-tuple fuzzy linguistic representation are both suitable for the representation of subjectivity in expert estimations in the case of early design and ASIT. Therefore, we propose to use these two approaches to represent the subjective uncertainty and compare them to the initial results where subjectivity is not taken into account. Before integrating the two fuzzy methods into ASIT, the fuzzy techniques to be used should be defined, e.g., the operations of fuzzy sets, the selection of suitable membership functions, and the utilization of defuzzification methods. These issues are discussed in the next section.

4.4 Fuzzy Techniques for Representing Subjective Uncertainty in ASIT

Many different fuzzy membership functions exist. It is not possible and not appropriate to test all of them in this work. Therefore, it is necessary to identify the most appropriate membership function within our research context. In addition, the simplification for fuzzy number operations should also be investigated, since operations such as the multiplication of several fuzzy members can be very tedious.

A fuzzy number is a special fuzzy set $N = \{(x, \mu_N(x)), x \in R\}$ where x is a real value $R_1 : -\infty < X < +\infty$ and $\mu_N(x)$ is a continuous mapping from R_1 to $(0, 1)$ (Haq & Kannan, 2006). Operations of fuzzy numbers can be defined based on the extension principle proposed by Zadeh (1975). If \tilde{M} and \tilde{N} are fuzzy numbers, membership of $\tilde{M}(*)\tilde{N}$ is defined as follow (Gao, Zhang, & Cao, 2009) :

$$\mu_{\tilde{M}(*)\tilde{N}}(z) = \sup_{z=x*y} \min\{\mu_{\tilde{M}}(x), \mu_{\tilde{N}}(y)\} \quad (1)$$

Where * stands for any of the four algebraic operations including addition, subtraction, multiplication and division.

Fuzzification is the process of making a crisp quantity fuzzy (Ross, 2009, p. 93), which is normally the first step in using fuzzy set theory. The main objective of fuzzification is to define a membership function for each fuzzy quantity. The most commonly used membership functions for linguistic terms are triangular, trapezoidal, left shoulder, right shoulder, Gaussian and Sigmoid (Garibaldi & John, 2003). Among the various shapes of membership functions, the triangular membership function has been frequently used in many fuzzy set applications (Pedrycz, 1994). Chou and Chang (Pedrycz, 1994) have explained the reason of the popularity of the triangular membership function: “Undoubtedly, if the semantics of a certain linguistic term has to be specified, then the simplest form of the membership function one could think of would be to provide a modal (typical) value of the considered term along with the lower and upper bounds. The distribution of the grades of membership between these boundaries is then linear – an acceptance of any other form of relationship to bear some legitimacy may definitely call for some auxiliary information about the membership values to be furnished at the selected intermediate points distributed within these bounds.” In this paper, we propose to use the triangular fuzzy membership function mainly because of the lack of information in early conceptual design stage. As presented previously, experts use predefined linguistic terms and numerical levels to give their estimation. Therefore, we have two types of information for defining a fuzzy membership function: (1) the estimation that is given by a group of experts; (2) the predefined numerical levels, and the distance between the levels. When using the triangular membership function, we can assign the expert estimation as the mode of the triangular fuzzy number, and twice the distance between two adjacent levels as the support. To the best of our knowledge, other types of membership functions all require more information than this. Therefore, we propose to use the triangular membership function to model experts’ subjective uncertainty in ASIT in early conceptual design stage.

The basic features of triangular fuzzy numbers can be found in the work of Dubois and Prade (1978), and the basic operations can be found in the work of Chou and Chang (2008). A triangular fuzzy number can be denoted as $N = (l, m, u)$, its membership function $\mu_N(x) : R \rightarrow [0,1]$ is represented as (Chang, 1996):

$$\mu_N(x) = \begin{cases} \frac{1}{m-l}x - \frac{1}{m-l}, & x \in [l, m], \\ \frac{1}{m-u}x - \frac{u}{m-u}, & x \in [m, u], \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Where $l \leq m \leq u$, l , m and u are the lower bound of the support, the core, and the upper bound of the support of N , respectively.

Given two triangular fuzzy numbers $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$, operations of fuzzy numbers are shown below:

Addition of two fuzzy numbers \oplus :

$$\tilde{A} \oplus \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (3)$$

Addition of a real number k and a fuzzy number \oplus :

$$k \oplus \tilde{B} = (k + b_1, k + b_2, k + b_3) \quad (4)$$

Multiplication of a real number k and a fuzzy number \otimes :

$$k \otimes \tilde{B} = (kb_1, kb_2, kb_3) \quad (5)$$

Although the multiplication of a real number and a fuzzy triangular number is easy to calculate, the higher level operation (i.e., multiplication of two or several fuzzy numbers) is cumbersome with insurmountable computational effort (Triantaphyllou, 2000). Gao et al. (2009) demonstrated that the result from multiplication of two triangular fuzzy numbers is not a triangular fuzzy number, and the result can be obtained by using nonlinear programming method, analytical method, computer drawing method and computer simulation method. Gao et al. (2009) demonstrated that by using analytical method, for two triangular fuzzy numbers such as $\tilde{A} = (a_1, a_2, a_3)$, $\tilde{B} = (b_1, b_2, b_3)$, the membership function of $\tilde{N} = \tilde{A}(\times)\tilde{B}$ is:

$$\mu_{\tilde{N}}(x) = \begin{cases} \frac{-(a_1b_2 + b_1a_2 - 2a_1b_1) + \sqrt{(a_1b_2 - b_1a_2)^2 + 4(a_2 - a_3)(b_2 - b_1)x}}{2(a_2 - a_1)(b_2 - b_1)}, & a_1b_1 \leq x \leq a_2b_2 \\ \frac{-(a_3b_2 + b_3a_2 - 2a_3b_3) - \sqrt{(a_3b_2 - b_3a_2)^2 + 4(a_2 - a_3)(b_2 - b_3)x}}{2(a_2 - a_3)(b_2 - b_3)}, & a_2b_2 \leq x \leq a_3b_3 \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

One can notice that the multiplication of several fuzzy numbers requires significant computational effort to obtain precise results. Therefore, in order to facilitate its application in engineering problems, a simplified formula is usually used (Chiou, Tzeng, & Cheng, 2005; Tzeng & Huang, 2011):

$$\tilde{A} \otimes \tilde{B} \cong (a_1b_1, a_2b_2, a_3b_3) \quad (7)$$

In decision making problems, usually a single scalar is preferred as output of a fuzzy process in order to facilitate ranking or selection. To transform fuzzy results into a scalar, defuzzification is performed. Defuzzification is defined as a mapping of fuzzy sets to elements of the universe considered significant with respect to this fuzzy set (Runkler, 1997). Widely used defuzzification methods are maximum (max) membership principle, centroid method, weighted average method, mean max membership, center of sums, and center of largest area (Ross, 2009). Within the context of this study, the triangular fuzzy membership functions are used, which are peaked output functions with their maximum equal to the "significant element". Since in peaked output functions, the max membership principle is commonly used (Ross, 2009), we propose to use this defuzzification method in the 2-tuple linguistic representations. The max membership principle is given by the expression (Ross, 2009):

$$\mu_{\tilde{A}}(z^*) \geq \mu_{\tilde{A}}(z), \text{ for all } z \in Z \quad (8)$$

Where z^* is the defuzzified value.

In the 2-tuple linguistic representation, the single number obtained from defuzzification is transformed again to the initial expression domain (i.e., the predefined linguistic terms). The 2-tuple linguistic representation uses a 2-tuple (s, α) to represent the results, where s refers to the closest linguistic of the information, α is a numerical value expressing the value of the translation from the original result to the closest linguistic term (Herrera & Martinez, 2000).

Definition: Let $S = \{s_0, \dots, s_g\}$ be a linguistic term set and $\beta \in [0, g]$ a value representing the result of a symbolic aggregation operation. Then, the 2-tuple that expresses the equivalent information to β , which is obtained with the following function (adopted from Herrera & Martinez, 2000):

$$\Delta: [0, g] \rightarrow S \times [-0.5\delta i, 0.5\delta i] \quad (9)$$

$$\Delta(\beta) = (s_i, \alpha), \text{ with } \begin{cases} s_i, & i = \text{round}(\beta) \\ \alpha = \beta - i, & \alpha \in [-0.5\delta i, 0.5\delta i] \end{cases} \quad (10)$$

Where $\text{round}(\cdot)$ is the usual round operation, s_i has the closest term to " β ", and " α " is the value of the symbolic translation. δi is the gap between i and $i-1$ for $i \in \{1, 2, \dots, g\}$.

Because of the lack of additional information in early conceptual design stage, the isosceles triangular membership function issued in this work. We assume that the support of the triangular fuzzy number is twice the predefined scale, which indicates the assumption that the group of experts are able to choose the correct linguistic term. In case of greater or smaller subjective uncertainty, the support of the triangular fuzzy number can also be changed, but the principle and the reasoning of this work remains the same, and the results obtained in this work will not be greatly influenced.

In the next section, the two fuzzy methods are integrated into ASIT by using a powertrain design case.

4.5 The Power Train Design Case

This powertrain design case is used to show the initial ASIT results, and the integration of subjective uncertainties by using the two selected fuzzy methods.

A powertrain is a system of mechanical parts in a vehicle that first provides energy, then converts it in order to propel the vehicle. Due to the increasing demand of lower emissions and higher fuel efficiency, the OEM plans to design a new powertrain for their motor vehicle to better satisfy market needs. Although the powertrain is normally an in-house subsystem, with only few modules outsourced (the battery and the engine for example), we assume in this case study that each module in the powertrain is planned to be outsourced to one supplier, for the purpose of illustration. The powertrain design case used

in this work is very similar to the one used in Ye et al. (2014), the data used is the same except the added uncertainty information shown in Figure 6. See (Ye et al., 2014) for more information about ASIT and the powertrain design case.

4.5.1 ASIT without Considering Subjective Uncertainty

In phase 1 and 2 in ASIT, the satisfaction of new customer needs by existing products is estimated, the modules that should be improved are identified, and new modules are found. In phase 3, experts start providing estimation on satisfaction levels and uncertainties, after the generation of all possible architectures in which new modules are integrated. Since the subjective uncertainty studied in this work is caused by expert estimation, we decided to focus on phases 3, 4, and 5 in this case study because of space limitation. Please see Ye et al. (2014) for further information about the other phases of ASIT.

We assume that modules that can potentially sufficiently satisfy new requirements are found. All possible architectures with integration of these new modules are generated, as shown in Fig.4-2. The number “1” represents that the module belongs to the architecture, while the “0” represents the module does not belong to the architecture.

		Possible architecture 1	Possible architecture 2	Possible architecture 3	Possible architecture 4	Possible architecture 5	Possible architecture 6	Possible architecture 7	Possible architecture 8	Possible architecture 9	Possible architecture 10	Possible architecture 11	Possible architecture 12
Modules	Engine 1	1	0	0	0	1	0	0	0	1	0	0	0
	Engine 2	0	1	0	0	0	1	0	0	0	1	0	0
	Engine 3	0	0	1	0	0	0	1	0	0	0	1	0
	Engine 4	0	0	0	1	0	0	0	1	0	0	0	1
	Battery 1	1	1	1	1	0	0	0	0	0	0	0	0
	Battery 2	0	0	0	0	1	1	1	1	1	0	0	0
	Battery 3	0	0	0	0	0	0	0	0	1	1	1	1
	Transmission 1	1	1	1	1	1	1	1	1	1	1	1	1
	Electric motor 1	1	1	1	1	1	1	1	1	1	1	1	1
	Driveshaft 1	1	1	1	1	1	1	1	1	1	1	1	1
	Final drive 1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 4-2 Generation of all possible architectures

In phase 3, in order to calculate the overall uncertainty and satisfaction level of each architecture, estimations are provided by experts. Since the structure of the product is complex and the requirements vary from project to project, it is difficult for experts to estimate how well a product satisfies a requirement directly. In comparison, it is much easier to estimate how well a module satisfies a function, as shown in Fig.4-3. The numbers in Fig.4-3 represent satisfaction levels defined in Tab.4-1. For example, the “engine 1” is a “weak solution” for satisfying the function “respect environment”. Therefore, using the information in Tab.4-1, the satisfaction level 2 is assigned to this estimation. Since the significant figures include all the precise digits and the first estimated digit (Serway & Jewett, 2013), we keep two significant figures for the estimation.

$M_{fun-mod}$		Modules										
		Engine 1	Engine 2	Engine 3	Engine 4	Battery 1	Battery 2	Battery 3	Transmission 1	Electric motor 1	driveshaft: 1	Final drive: 1
Functions	Respect environment	2.0	4.0	5.0	6.0	8.0	8.0	9.0	0	0	0	0
	Economize fuel	2.0	4.0	5.0	6.0	10.0	10.0	10.0	0	0	0	0
	Provide power	8.0	6.0	6.0	5.0	2.0	5.0	8.0	0	0	0	0
	Transform energy to torque	0	0	0	0	0	0	0	8.0	6.0	0	0
	Transmit torque to final drive	0	0	0	0	0	0	0	0	0	8.0	0
	Interact with surface	0	0	0	0	0	0	0	0	0	0	8.0
	Accept recharge	0	0	0	0	1.0	6.0	8.0	0	0	0	0

Figure 4-3 Function satisfaction level by modules

Then, by using the composition of architectures (Fig.4-2), the “satisfaction of functions by modules” is propagated to the “satisfaction of functions by architectures”. For simplicity, we assume that how an architecture satisfies a function depends on how the modules in the architecture satisfy the function. The satisfaction level of a function by an architecture is defined as the average of its modules’ satisfaction levels of this function.

The “satisfaction of functions by architectures” is then propagated to the “satisfaction of requirements by architectures” by using the relations between requirements and functions (Fig.4-4). The requirement – function relations in Fig.4-4 represent the percentage that a function satisfies a requirement. For example, the requirement “CAFE standard” is satisfied 50% by the function “Economize fuel”, 50% by “provide power”.

M_1		Functions						
		Respect environment	Economize fuel	Provide power	Transform energy to torque	Transmit torque to final drive	Interact with surface	Accept recharge
Requirements	CAFE standard	0	0.5	0.5	0	0	0	0
	Acceleration time	0	0	0.6	0.2	0.2	0	0
	Cruising velocity at grade	0	0	0.7	0	0	0.3	0
	0-60 mph time	0	0	1	0	0	0	0
	Low greenhouse gas emission	1	0	0	0	0	0	0
	Rechargeable by external electric power	0	0	0	0	0	0	1

Figure 4-4 Requirement-function relations

For propagating the satisfaction of functions to the satisfaction of requirements, we have used:

$$M_{req-arch} = M_1 \times M_{fun-arch} \quad (11)$$

Assuming equal importance of the requirements (this assumption can be changed if needed), an overall requirements satisfaction score is obtained for each of the possible architectures by calculating the average

(Fig.4-5). This score represents how well the architecture satisfies the entire requirements (with a 1-10 scale). We round the final result to two significant figures.

Architecture	1	2	3	4	5	6	7	8	9	10	11	12
Satisfaction	4.7	4.5	4.6	4.5	6.3	6.1	6.2	6.1	7.4	7.2	7.3	7.2

Figure 4-5 Requirements satisfaction (without considering expert uncertainty)

The overall uncertainty of an architecture is calculated based on uncertainty of modules (M5 in Fig.4-6), compatibility between modules (M4), and uncertainty of suppliers' capabilities (M6). In addition, the matrix M3 represents the supplier of each module. Since the uncertainties and compatibilities can all be considered as probabilities, "the overall uncertainty of an architecture" is defined as the product of all its modules' uncertainties, its suppliers' uncertainties, and the compatibilities between its modules (because of the independence of probabilities). Experts provide their estimations by using the linguistic terms defined in Tab.4-2. These linguistic terms are then converted to related numerical scales.

M ₅										M ₆												
1	1	0.80	0.70	1	0.90	0.50	1	1	1	1	Uncertainty			1	0.70	0.90	1	0.50	1	1	1	1
Engine 1	Engine 2	Engine 3	Engine 4	Battery 1	Battery 2	Battery 3	Transmission 1	Electric motor 1	driveshaft 1	Final drive 1	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6	Supplier 7	Supplier 8	Supplier 9			
				0.20	0.10	0.30	1	0.30	1	1	Engine 1	1	0	0	0	0	0	0	0	0	0	0
				1	0.70	0.50	1	1	1	1	Engine 2	1	0	0	0	0	0	0	0	0	0	0
				0.50	0.90	0.80	0.90	0.80	0.90	0.90	Engine 3	0	1	0	0	0	0	0	0	0	0	0
				0.50	0.80	0.90	0.90	0.90	0.80	0.90	Engine 4	0	0	1	0	0	0	0	0	0	0	0
0.20	1	0.50	0.50				1	1	1	1	Battery 1	0	0	0	1	0	0	0	0	0	0	0
0.10	0.70	0.90	0.80				0.80	0.90	0.90	0.90	Battery 2	0	0	0	1	0	0	0	0	0	0	0
0.30	0.50	0.80	0.90				0.90	0.90	0.90	0.90	Battery 3	0	0	0	0	1	0	0	0	0	0	0
1	1	0.90	0.90	1	0.80	0.90	1	1	1	1	Transmission 1	0	0	0	0	0	1	0	0	0	0	0
0.30	1	0.80	0.90	1	0.90	0.90	1	1	1	1	Electric motor 1	0	0	0	0	0	0	1	0	0	0	0
1	1	0.90	0.80	1	0.90	0.90	1	1	1	1	Driveshaft 1	0	0	0	0	0	0	0	1	0	0	0
1	1	0.90	0.90	1	0.90	0.90	1	1	1	1	Final drive 1	0	0	0	0	0	0	0	0	0	1	0

Figure 4-6 Uncertainty information

The overall uncertainties of possible architectures are shown in Fig.4-7, which represents the percentage that an architecture can be developed without any problem. The confidence that one company has on the capabilities of a given supplier is also integrated in this overall uncertainty.

Architecture	1	2	3	4	5	6	7	8	9	10	11	12
Uncertainty	0.060	1	0.16	0.18	0.020	0.37	0.15	0.15	0.010	0.080	0.040	0.050

Figure 4-7 Uncertainty (without considering expert uncertainty)

4.5.2 Taking into Account Subjective Uncertainty in ASIT

4.5.2.1 Using Type-1 Fuzzy Sets

One approach that has been identified as suitable for representing subjective uncertainty is the Type-1 Fuzzy Sets. Using this method, each expert's estimation of satisfaction levels (using Tab.4-1) is converted to a $\tilde{I}-\tilde{10}$ fuzzy number scale. The isosceles triangular membership functions are used as shown in Fig.4-8. These fuzzy numbers are then aggregated by using fuzzy operations defined in section 4.

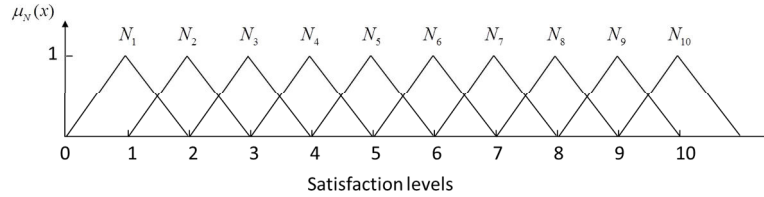


Figure 4-8 Fuzzy numbers for satisfaction levels

Let us take the satisfaction of requirement “CAFE standard” by architecture 6 as an example to demonstrate the calculation. In order to calculate how the architecture 6 satisfies the requirement “CAFE standard”, the functions “Economize fuel” and “Provide power” need to be considered since they each satisfy 50% of this requirement (Fig.4-4). The possible architecture 6 is composed of modules “engine 2”, “battery 2”, “transmission 1”, “electric motor 1”, “driveshaft 1”, and “final drive 1”. In order to calculate how the architecture satisfies the function “Economize fuel”, we need to calculate the average of how the engine 2 and the battery 2 satisfy this function. Therefore:

$$\begin{aligned} FSL_2 &= (0.5 \times 4) \oplus (0.5 \otimes (9, 10, 11)) \\ &= 2 \oplus (4.5, 5, 5.5) = (6.5, 7, 7.5) \end{aligned}$$

Here, the satisfaction level “4” is not converted to fuzzy number, since the engine 2 is an existing module. Therefore, the information of engine 2 comes from previous projects, instead of expert estimation, so that the subjective uncertainty is not considered. Using the same principle, satisfaction of function “Provide power” can be calculated. Then, the satisfaction of requirement “CAFE standard” can be calculated by:

$$\begin{aligned} RSL_1 &= (0.5 \otimes (6.5, 7, 7.5)) \oplus (0.5 \otimes (5, 5.5, 6)) \\ &= (3.25, 3.5, 3.75) \oplus (2.5, 2.75, 3) \\ &= (5.75, 6.25, 6.75) \end{aligned}$$

Assuming equal importance of the requirements (which can be changed in necessary), an overall requirements satisfaction score is obtained by calculating the average for each possible architecture (shown in Fig.4-9).

Architecture	1	2	3	4
Satisfaction	4.7	4.5	{4.3,4.6,5.0}	{4.2,4.5,4.9}
Architecture	5	6	7	8
Satisfaction	{5.7,6.3,6.8}	{5.5,6.1,6.6}	{5.3,6.2,7.1}	{5.2,6.1,7.0}
Architecture	9	10	11	12
Satisfaction	{6.9,7.4,7.9}	{6.6,7.2,7.7}	{6.4,7.3,8.2}	{6.3,7.2,8.1}

Figure 4-9 Requirements satisfaction by using type-1 fuzzy sets (before values)

The requirements satisfactions obtained in Fig.4-9 can be illustrated using triangular fuzzy numbers as shown in Fig.4-10, with the threshold set at 6.

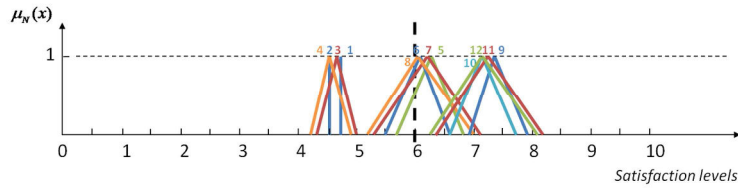


Figure 4-10 Requirements satisfaction by using type-1 fuzzy sets (membership functions)

In this case, it is obvious that architectures 1, 2, 3, and 4 are below the satisfaction threshold (since the entire fuzzy number is below the threshold), while architectures 9, 10, 11, and 12 are above the threshold. The situation for architectures 5, 6, 7, and 8 is more complicated, because they are partly above and partly below the threshold. We will discuss this kind of situations later in this chapter.

When estimating uncertainty of modules (M5), compatibility between modules (M4), and uncertainty of suppliers' capabilities (M6), probability levels are needed as given in Tab.4-2. In order to integrate subjective uncertainty, we convert each numerical level in Tab.4-2 into a triangular fuzzy number. The membership function of the fuzzy number set is shown in Fig.4-11. Since "0" represents "impossible" and "1" represents "certain", which both have precise definitions and thus have low fuzziness level, we keep them as crisp values during fuzzification.

The overall uncertainty of an architecture is defined as the product of all its modules' uncertainties, its suppliers' uncertainties and the compatibilities between the modules. Therefore, the multiplication of several triangular fuzzy numbers is needed. Simplified as described in section 4, the result achieved is shown in Fig.4-12.

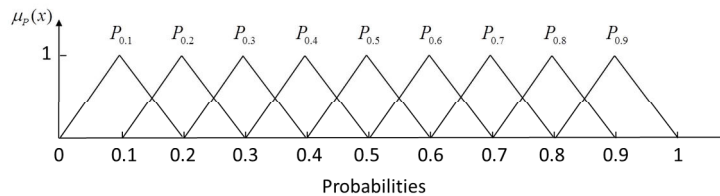


Figure 4-11 Fuzzy membership function for possibilities

Architecture	1	2	3	4
Uncertainty	0.060	1	{0.060,0.16,0.39}	{0.069,0.18,0.43}
Architecture	5	6	7	8
Uncertainty	{0,0.016,0.054}	{0.17,0.37,0.72}	{0.035,0.15,0.58}	{0.035,0.15,0.58}
Architecture	9	10	11	12
Uncertainty	{0.0039,0.015,0.043}	{0.026,0.082,0.22}	{0.0069,0.043,0.21}	{0.0090,0.054,0.26}

Figure 4-12 Uncertainty using type-1 fuzzy sets (values)

The illustration of the overall uncertainties is shown in Fig.4-13, with the threshold set at 0.1.

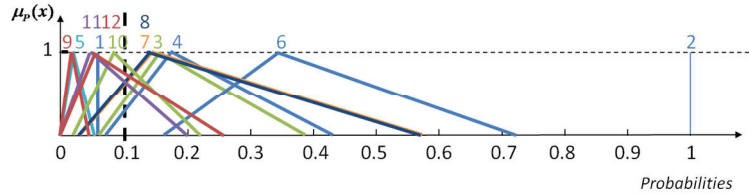


Figure 4-13 Uncertainty using type-1 fuzzy sets (membership functions)

In this case, it is quite obvious that architectures 1, 5, and 9 are below the threshold, while the architectures 2, 6, 3, 4, and 7 are above threshold. However, it is more difficult to define the situation of architectures 10, 11, and 12.

Now, we propose to focus on the fuzzy results that are partly above and partly below the threshold for both satisfaction levels and uncertainties, as shown in Fig.4-14.

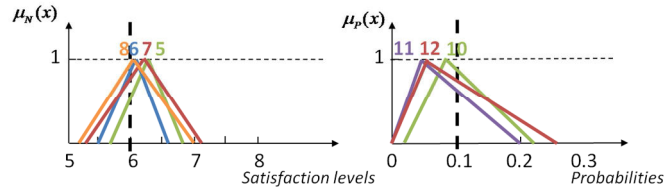


Figure 4-14 fuzzy results that are partly above the threshold

The utilization of fuzzy methods is to the purpose of considering fuzziness in human estimation, which is also represented in the results shown in Fig.4-14. Therefore, when considering whether these results pass the threshold, the fuzziness should also be considered, which means that the belongingness of these results to the set that passes the threshold is also fuzzy. Therefore, we think that each of these results should have a degree of “passing the threshold”, and whether the architecture or supplier belongs to the identified architecture or supplier depends on decision maker’s tolerance about the result.

There are many ways to represent decision makers’ tolerance level. In this work, as an example, we use the α -cut to represent the tolerance, and define that the result passes the threshold if the maximum value of the fuzzy number after the α -cut passes the threshold. With this definition, the decision totally depends on the value of α — which represents the tolerance level of the decision maker (bigger α is, smaller the tolerance is).

For example, if we set α at 0.7 for the overall uncertainty as shown in Fig.4-15, the architectures 10 and 12 will pass the threshold and the architecture 11 does not pass the threshold.

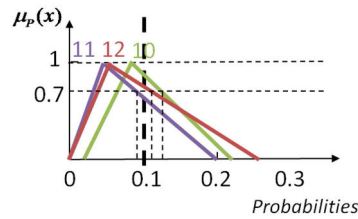


Figure 4-15 Using α -cut to represent tolerance level

However, the purpose of using the α -cut is only to show that these kinds of fuzzy results should be considered fuzzy regarding their belonging to the identified candidates. They can be boss below or above the threshold regarding decision makers' tolerance. Therefore, in architecture and supplier identification results, we represent this kind of candidates as “possible candidates depend on tolerance level”.

4.5.2.2 Using 2-Tuple Fuzzy Linguistic Representation

The 2-tuple fuzzy linguistic representation is exactly the same as the type-1 fuzzy sets from fuzzification until obtaining fuzzy results (shown in Fig.4-9 and Fig.4-12). After obtaining fuzzy results, the 2-tuple fuzzy linguistic representation defuzzifies the results, and converts the defuzzification result back to the closest initial linguistic terms, and the distance between the original results to the closest linguistic term.

According to the reasoning in section 4, the max membership principle is used for defuzzification, and the results are shown in Fig.4-16 and Fig.4-17.

Architecture	1	2	3	4	5	6	7	8	9	10	11	12
Satisfaction	4.7	4.5	4.6	4.5	6.3	6.1	6.2	6.1	7.4	7.2	7.3	7.2

Figure 4-16 Requirements satisfaction after defuzzification

Architecture	1	2	3	4	5	6	7	8	9	10	11	12
Uncertainty	0.060	1	0.16	0.18	0.020	0.37	0.15	0.15	0.010	0.080	0.040	0.050

Figure 4-17 Uncertainty after defuzzification

When using the 2-tuple fuzzy linguistic representation, a 2-tuple is (s, α) used, where s represents the closest linguistic term, and α represents the distance. For example, the overall requirements satisfaction level of architecture 1 is equal to 4.7 (see Fig.4-16), its closest linguistic terms is represented by the level 5, which is “a satisfactory solution”. The distance between 4.7 and 5 is equal to -0.3. That is why in 2-tuple fuzzy linguistic representation, the overall requirements satisfaction level of architecture 1 is $(N5, -0.3)$. The results of requirement satisfaction and uncertainty by using the 2-tuple fuzzy linguistic representation are shown in Fig.4-18 and Fig.4-19, respectively.

Architecture	1	2	3	4	5	6
Satisfaction	(N5,-0.3)	(N5,-0.5)	(N5,-0.4)	(N5,-0.5)	(N6,0.3)	(N6,0.1)
Architecture	7	8	9	10	11	12
Satisfaction	(N6,0.2)	(N6,0.1)	(N7,0.4)	(N7,0.2)	(N7,0.3)	(N7,0.2)

Figure 4-18 Requirements satisfaction using 2-tuple linguistic representation

Architecture	1	2	3	4	5	6
Uncertainty	(P _{0.1} , -0.040)	(1, 0)	(P _{0.2} , -0.04)	(P _{0.2} , -0.02)	(0, 0.016)	(P _{0.4} , -0.03)
Architecture	7	8	9	10	11	12
Uncertainty	(P _{0.2} , -0.05)	(P _{0.2} , -0.05)	(0, 0.015)	(P _{0.1} , -0.018)	(0, 0.043)	(P _{0.1} , -0.046)

Figure 4-19 Uncertainty using 2-tuple fuzzy linguistic representation

4.6 Comparison of Results and Discussion

In section 5, we obtained the requirements satisfaction levels and uncertainties for each of the architectures. The threshold is set at 6 or N6 for satisfaction levels and 0.1 or P0.1 for uncertainty to filter the generated architectures. The potential supplier identification results obtained without considering subjective uncertainty, considering subjective uncertainty by using type-1 fuzzy sets and 2-tuple linguistic representation are compared in Fig.4-20.

Without Integrating Expert Uncertainty			
(Clustering: satisfaction \geq 6, uncertainty \geq 0.1)			
Architecture	Satisfaction	Uncertainty	Supplier
6	6.1	0.37	1,4,6,7,8,9
7	6.2	0.15	2,4,6,7,8,9
8	6.1	0.15	3,4,6,7,8,9
Integrating Expert Uncertainty with type-1 fuzzy sets			
(Clustering: satisfaction \geq 6, uncertainty \geq 0.1)			
Architecture	Satisfaction	Uncertainty	Supplier
6	(5.5,6.1,6.6)	(0.17,0.37,0.72)	1,4,6,7,8,9
7	(5.3,6.2,8.1)	(0.035,0.15,0.58)	2,4,6,7,8,9
8	(5.2,6.1,7.0)	(0.035,0.15,0.58)	3,4,6,7,8,9
10	(6.6,7.2,7.7)	(0.026,0.082,0.22)	1,5,6,7,8,9
11	(6.4,7.3,8.2)	(0.0069,0.043,0.21)	2,5,6,7,8,9
12	(6.3,7.2,8.1)	(0.0090,0.054,0.26)	3,5,6,7,8,9
Integrating Expert Uncertainty with 2-tuple fuzzy linguistic representation			
(Clustering: satisfaction \geq N ₆ , uncertainty \geq P _{0.1})			
Architecture	Satisfaction	Uncertainty	Supplier
6	(N ₆ ,0.1)	(P _{0.4} , -0.03)	1,4,6,7,8,9
7	(N ₆ ,0.2)	(P _{0.2} , -0.05)	2,4,6,7,8,9
8	(N ₆ ,0.1)	(P _{0.2} , -0.05)	3,4,6,7,8,9
10	(N ₇ ,0.2)	(P _{0.1} , -0.018)	1,5,6,7,8,9
12	(N ₇ ,0.2)	(P _{0.1} , -0.046)	3,5,6,7,8,9

Figure 4-20 Comparison of supplier identification results

Upon comparison of the results, we can see that without considering subjective uncertainty, ASIT identifies three architectures (architectures 6, 7 and 8), which are also identified with consideration of subjective uncertainty using the two fuzzy methods.

When using type-1 fuzzy sets, three “possible architectures depend on tolerance level” are also identified (number 10, 11 and 12). Whether these three architectures belong to the identified architectures depends on the decision makers’ tolerance level.

When using the 2-tuple fuzzy linguistic representation, aside from architectures 6, 7 and 8, two additional architectures (10, 12) are identified. This expansion of the result scope is because that the 2-tuple fuzzy linguistic representation converts the defuzzification result to the initial linguistic terms, which rounds up the results, thus increases the tolerance level.

From the comparison one can observe that (1) the architectures and suppliers identified without considering subjective uncertainty are also identified with consideration of subjective uncertainty by using the two fuzzy methods; (2) considering subjective uncertainty enlarges the result scope mainly because the consideration of subjective uncertainty increases the level of tolerance (i.e. more tolerant) when filtering candidates.

However, the tolerance level can also be changed without considering subjective uncertainty, and by simply changing the thresholds. As shown in Fig.4-21, by changing the uncertainty threshold to 0.05, the same result scope can be obtained as integrating subjective uncertainty using 2-tuple linguistic representation. By changing the uncertainty threshold to 0.04, same results can be obtained as using type-1 fuzzy sets to model subjective uncertainty.

Without Integrating Expert Uncertainty

Satisfaction threshold	Uncertainty threshold	Identified architecture	Identified supplier
6	0.1	6	1,4,6,7,8,9
		7	2,4,6,7,8,9
		8	3,4,6,7,8,9
6	0.05	6	1,4,6,7,8,9
		7	2,4,6,7,8,9
		8	3,4,6,7,8,9
		10	1,5,6,7,8,9
		12	3,5,6,7,8,9
6	0.04	6	1,4,6,7,8,9
		7	2,4,6,7,8,9
		8	3,4,6,7,8,9
		10	1,5,6,7,8,9
		11	2,5,6,7,8,9
		12	3,5,6,7,8,9

Figure 4-21 Changing thresholds without considering subjective uncertainty

According to the analysis above, we found that (1) the result of ASIT without considering subjective uncertainty is reliable because the identified architectures are also within the result scope with

consideration of subjective uncertainty; (2) same results as considering subjective uncertainty can be obtained without considering subjective uncertainty by simply changing the value of thresholds. Therefore, we conclude that the consideration of subjective uncertainty does not considerably influence ASIT results, so that it is not necessary to consider the subjective uncertainty in ASIT in early conceptual design stage.

However, it is very important to note that this conclusion is obtained under the situation of using triangular membership functions and which is due to the lack of information in early conceptual design stage. In other design stages, this conclusion may not valid since when more information is available, other types of fuzzy membership functions can be used, which may lead to different results. This result also points out that under certain situation, it is not useful to consider expert estimation uncertainty. Considering expert estimation uncertainty without analyzing the situation may result in waste of effort.

There are still several limitations in this work. Firstly, although the max membership principle is demonstrated as a proper choice for defuzzification, it is still interesting to test other defuzzification methods, which may lead to different outcomes. Secondly, we assumed that using a group of experts is able to correct the cognitive bias of each expert. However, the cognitive bias is still an interesting issue that is worth investigating further under the topic of expert uncertainty. In addition, this work is carried out specifically in the context of ASIT. It may benefit from a generalization to a broader context.

4.7 Conclusions

Due to innovation integration in early design phases, aside from previous project data, expert estimations are often used. In this work, we investigated how subjective uncertainty resulting from expert estimations influences the result of ASIT, which is an early design support tool proposed in our previous work. It is important to understand to what extent this approach can be used, and can yield robust results in industrial context, and whether it is necessary to consider subjective uncertainty in ASIT.

After analysing different uncertainty representation methods for subjective uncertainty, both Type-1 and 2-tuples fuzzy sets have been found suitable for representing this type of uncertainty in ASIT. A powertrain design case has been used to compare the results of the original ASIT and the results with integration of subjective uncertainties. The comparison shows that considering subjective uncertainty enlarges the result set (more architectures and suppliers are identified) because the consideration of subjective uncertainty increases the level of tolerance (i.e. more tolerant) when filtering candidates. However, the initial set without considering subjective uncertainty is found in this larger set, and same results as considering subjective uncertainty can be obtained without considering subjective uncertainty by simply changing the value of thresholds. Therefore, considering subjective uncertainty in ASIT will not have a considerable impact on the overall ASIT results, so that it is unnecessary to consider subjective uncertainty in ASIT in early conceptual design stage.

The result of this work is only valid in the context of early conceptual design, where information is extremely lacking, so that only triangular membership function can be used. The result also pointed out

that it is not always necessary to consider expert estimation uncertainty. Before considering this type of uncertainty, the context should be analysed to prevent the waste of effort.

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5

Paper #3. Integration of Environmental Impact Estimation in System Architecture & Supplier Identification

Submitted to:

Research in Engineering Design

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Abstract. With the emergence of environmental legislations in many countries, the importance placed upon environmental protection has been raised to a new level, especially for industrial activities. Considering environmental issues as early as possible, starting with the design stage, is expected in order to better manage and diminish environmental impact. Commensurate progress has been made in method/tool development for use in environmental impact estimation; however, very few of these methods allow integrating this estimation early in the design process – a critical point of deciding for potential product concepts and suppliers. In this paper, we propose a tool that integrates environmental impact estimation into architecture and supplier identification, in order to conjointly consider requirements satisfaction as well as uncertainty due to new module and new supplier integration. This tool is developed to support OEM (Original Equipment Manufacturer) decision-making in the context of an extended enterprise. A case study is presented to illustrate a plausible implementation.

Keywords. environmental impact estimation, architecture generation, supplier identification, early design stages

5.1 Introduction

Industrial activity has long been blamed for many of the environmental problems (Humphreys, Wong, & Chan, 2003). The current understanding is that becoming environment-friendly not only enables companies to create new business but also lower costs (Nidumolu, Prahalad, & Rangaswami, 2009). Attesting to this, Drumwright's data (1994) shows that in the U.S., 75% of consumers say that their purchasing decisions are affected by a company's environmental reputation, and 80% say that they would pay more for environment-friendlier goods. At the same time, because of the emergence of environmental legislations (e.g., The Waste Electrical & Electronic Equipment Directive (WEEE) of European Union), some non-environment-friendly products may now cost companies a lot to dispose (e.g., lithium batteries for pay phones, bought by British Telecom) (Lamming & Hampson, 1996). Being "green and competitive" is increasingly adopted as the win-win position (Porter & Linde, 1995); companies around the world have changed their way of purchasing, developing products, and marketing as they adopt this position as their corporate strategy (Sharma, 2000; Pujari, Wright, & Peattie, 2003; Drumwright, 1994).

In order to control the overall environmental impact of a product/system, it is widely recognized that OEMs (Original Equipment Manufacturers) should take the environmental issues into account early during the design of the product/system (Bhamra et al., 1999). However, current environmental impact estimation methods lack capabilities for considering new customer requirements, new modules, and new suppliers simultaneously.

In our previous works, we proposed an Architecture & Supplier Identification Tool (ASIT) for early design, which aims at controlling overall uncertainty and product requirements satisfaction, with simultaneous consideration of new requirements, modules, and suppliers. In this paper, we further enhance ASIT by adding an environmental impact estimation capability, in order to respond to the growing need of environmental protection. As shown in Fig.5-1, the Architecture & Supplier Identification Tool with Environmental impact estimation (ASIT-E) proposed in this paper takes three main inputs (i.e., new requirements, new modules, and new suppliers) to generate all possible architectures and to identify best suppliers. Input used is partly from data on previous projects, and partly from expert estimation and suppliers. Three thresholds (i.e., environmental impact, requirements satisfaction, and project uncertainty) are used to filter architectures and suppliers in order to provide a list of qualified candidates for further negotiation and selection.

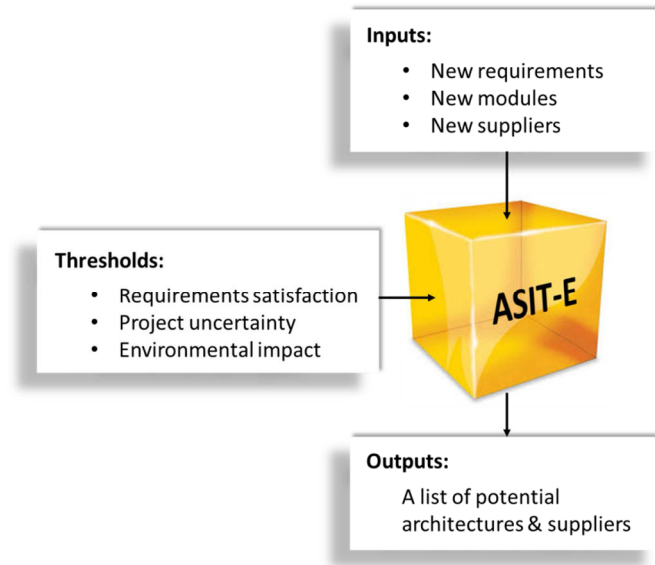


Figure 5-1 Overview of ASIT-E

In this paper, we first introduce the relevant background in section 5.2, including summaries on pertinent works, environmental directives and indicators along with a delineation of research focus. In section 5.3, an overview of ASIT-E is provided before a powertrain design case is used to demonstrate the proposed tool in section 5.4. In section 5.5, ASIT-E is compared to ASIT to show the influence on architecture and supplier identification results when environmental issues are considered. In section 5.6, the results are discussed before conclusions are provided in sections 5.7.

5.2 Background

Grisel & Duranthon (2001), in their book, suggested that in order to tackle environmental issues globally, a combination of a lifecycle method and a multi-criteria method should be used. Considering entire product lifecycle avoids shifting environmental impact downstream (i.e., lowering of environmental impact in one step may exacerbate the problem in another step), while using multi-criteria methods helps to consider impacts from all sources. The ASIT-E considers the entire lifecycle of a product and uses carefully identified environmental indicators to reflect possible environmental problems in each lifecycle phase.

5.2.1 Consideration of environmental issues in architecture and supplier identification

In recent years, the consideration of environmental issues in supplier selection has attracted a lot of attention, as predicted by Lloyd (1994):“In the future, environmental pressures will increase. Social, economic, business, financial and legal measures are going to force companies to set up environmental management systems. They will have to include as a key sub-system the appraisal and monitoring of suppliers.” Given this attention, several methods and tools have been proposed. For example, Humphreys

et al. (2003) identified quantitative and qualitative environmental criteria that fall into 7 environmental categories, using which suppliers are selected. Handfield, Walton, Sroufe & Melnyk (2002) identified the top 10 criteria for supplier environmental performance, and the top 10 most easily assessed criteria based on interviews with companies. They propose to use Analytical Hierarchy Process (AHP) multi-criteria decision method to assess suppliers along environmental dimensions. Bai & Sarkis (2010) used other methods to make decisions under uncertainty for the supplier selection problem, namely grey system and rough set methodologies. In their methods, the “triple-bottom-line” selection factors (i.e., economic, environmental as well as social factors) are integrated. These authors mainly focus on identifying appropriate environmental factors and proposing/selecting multi-criteria decision making methods.

Based on our review of the literature, we assert that very few methods and tools consider product architecture possibilities as well as suppliers when dealing with environmental issues. We found only three research works that are closely related. Two of these, the works of Krikke, Bloemhof-Ruwaard & Van Wassenhove (2003) and Chung, Kremer & Wysk (2014) focus on selecting modular structures of products to optimize product lifecycle performances in a closed-loop supply chain environment. In these two studies, product components are fixed, and authors seek to group these components in different ways to form modules in order to optimize environmental as well as other performance measures. The third study, carried out by Taghaboni-Dutta, Trappey & Trappey (2010), proposed a platform where suppliers can upload their green parts, and OEMs can find environmental friendly alternatives for their products more easily.

Previously discussed literature underlines that when evaluating environmental impacts during design, existing methods mostly consider only existing technologies and components. However, early design phases are characterized by uncertainties and consideration of new possibilities, involving new technologies, new modules, and new suppliers. The necessity to innovate requires the consideration of new technologies and suppliers; thus, there is a need to allow evaluation (even if roughly) of new modules or suppliers.

5.2.2 Research focus: Product lifecycle phases

The European Union’s Waste Framework Directive (European Commission, 2008) requires that the EU member states apply the following waste¹ management activities in a priority order: 1) prevention², 2) preparing for re-use³, 3) recycling⁴, 4) other recovery⁵, and 5) disposal⁶.

¹ Waste: Any substance or object which the holder discards or intends or is required to discard (European Commission, 2008).

² Prevention: Measures taken before a substance, material or product has become waste, that reduce the quantity of waste, the adverse impacts of the generated waste on the environment and human health, or the content of harmful substances in materials and products (European Commission, 2008).

With increasing demand of waste management expressed by the above and other legislations as well as customers, the closed-loop production and supply chain have been attracting attention both in academia and industry. The closed-loop production is the kind of production process where EOL (end-of-life) products are re-used (at the level of parts, or entire product) or recycled (at the level of material), to produce new identical products. The closed-loop supply chain is the form of supply chain often used along with closed-loop production, where collection points and reverse-feed centres are built to collect and process EOL products (Georgiadis & Besiou, 2010).

As part of the environmental impact estimation tool proposed in this paper, we adopt the context of a closed-loop production and supply chain, as shown in Fig. 5-2. The lifecycle phases considered in ASIT-E are presented in the outside layer of frames. The ASIT-E supports customization through lifecycle phases; OEMs can choose to use a subset of the lifecycle phases proposed in Fig. 5-2, or adding other phases according to their domain of activity.

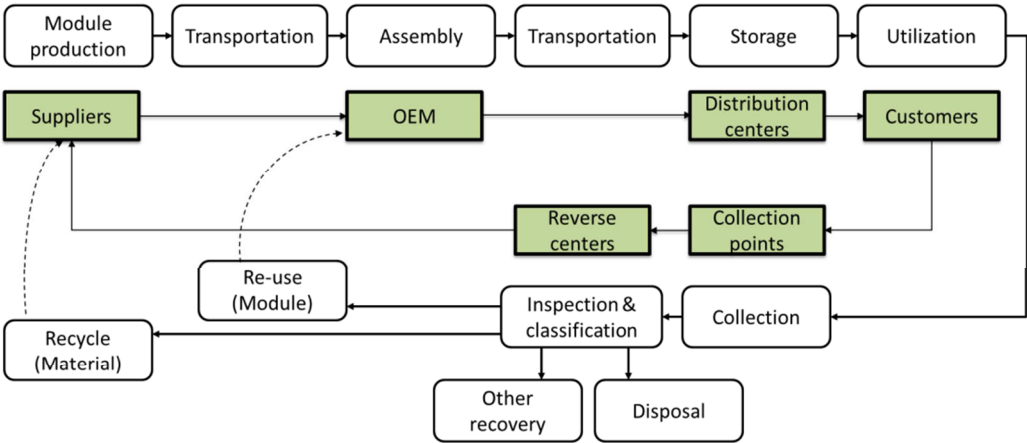


Figure 5-2 Product lifecycle phases considered in ASIT-E (Özkır & Başlıgıl, 2012)

³ Re-use: Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived (European Commission, 2008).

⁴ Recycling: Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes (European Commission, 2008).

⁵ Recovery: Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function, in the plant or in the wider economy (European Commission, 2008).

⁶ Disposal: Any operation which is not recovery even where the operation has as a secondary consequence of reclamation of substances or energy (European Commission, 2008).

Ideally modules are produced by suppliers using recycled materials, to be transported to the OEM. Assembly is carried out in OEM facilities, and transported to the distribution centre, and then to customers. The EOL products are collected at collection points and sent to reverse-feed centres, where reusable high quality modules are separated for minor repair, and then reuse in new products. Non-reusable parts are either recycled as material, sent for other recovery, or disposed.

5.2.3 Environmental directives & indicators

This section presents the environmental indicators used in ASIT-E, whose selection is informed by prior works. The selection of environmental indicators depends greatly on OEM's particular needs, including but not restricted to product category, local legislations, strategy, etc. Therefore, we aim at providing an idea of choosing suitable indicators, and demonstrate their utilization within ASIT-E; during their implementation, OEMs can freely choose other indicators since the structure of ASIT-E supports this flexibility.

In order to consider potential environmental impact sources comprehensively, both product architecture and supplier related environmental indicators should be considered. The supplier related indicators allow revealing environmental impact generated in the phases of manufacturing and supplier-OEM transportation, while the architecture related indicators consider the characteristic of a particular product concept (e.g., toxic material used), and its potential performance during utilization (e.g., consumption of electricity).

Regarding supplier related environmental indicators, we adopt indicators from the work of Handfield et al. (2002), where the top 10 criteria for supplier environmental performance have been identified based on interview sat companies. Normally, environmental performance of suppliers is evaluated by the procurement department, using a long list of criteria. This evaluation is usually carried out when the product concept is decided. However, in ASIT-E, the purpose is to weed out unqualified suppliers at the very early stages of product development, in parallel with concept definition. Therefore, we seek to identify the most important and easily accessible environmental indicators.

In the work of Handfield et al. (2002), six indicators are considered both important and easily accessible: (1) ISO 14001 certified, (2) use of ozone depleting substances, (3) use of EPA 17 hazardous materials, (4) environmental friendly packaging, (5) use of recycled material, and (6) public disclosure of environmental record. We regroup "use of ozone depleting substances" and "use of EPA 17 hazardous materials" into module related indicators since they are design/product specific. We consider the following four indicators in ASIT-E as supplier related indicators.

- 1) ISO 14001 certified
- 2) Environmental friendly packaging
- 3) Use of recycled material
- 4) Public disclosure of environmental record

In order to avoid environmental legislation violations by the eventual product, we abstracted indicators from legislations that the product must conform to. Although many governments have introduced environmental regulations and directives, we mainly focus on the European Union, and three specific directives that are most related to complex system development:

- 1) Waste Electrical & Electronic Equipment Directive (WEEE);
- 2) Restriction of Hazardous Substances Directive (RoHS);
- 3) European Eco-design Directive (Erp).

The WEEE (European Commission, 2014c) is the European Community directive on Waste Electrical and Electronic Equipment, which sets collection, recycling and recovery target for all types of electrical goods. This directive requires that, starting from 2016, the minimum collection rate shall be 45% of the total weight of WEEE collected in a given year. The percentage is calculated based on the average weight of EEE placed on the market in the three preceding years. The recovery rate and the recycle rate are also defined for each category of EEE for different periods. For example, for category 1 or 10, for the period between August 13, 2012 and August 14, 2015, the minimum recovery and recycling rate should be: 80% and 75%, respectively.

The RoHS (Restriction of Hazardous Substances Directive (European Commission, 2014b), newest version: 2011/65/EU) restricts the use of six hazardous materials in the manufacture of all types of electrical and electronic equipment. This directive restricts the use of the six substances with maximum concentration values tolerated by weight in homogeneous materials (see Fig. 5-3).

	Material	Maximum concentration rate (by weight)
1	Lead (Pb)	0.10%
2	Mercury (Hg)	0.10%
3	Cadmium (Cd)	0.01%
4	Hexavalent chromium (Cr ⁶⁺)	0.10%
5	Polybrominated biphenyls (PBB)	0.10%
6	Polybrominated diphenyl ether (PBDE)	0.10%

Figure 5-3 Restricted Materials by RoHS

The European Eco-design Directive (Directive 2009/125/EC (European Commission, 2014a)) aims at establishing a framework for setting eco-design requirements for “energy-related products”. The ultimate aim of this directive is to urge manufacturers of energy-using products to reduce the energy consumption and other negative environmental impacts of their products at the design stage. While the directive’s primary aim is to reduce energy use, it also aims at enforcing other environmental considerations, including: materials use, polluting emissions, waste issues, and recyclability.

Using the literature on these three directives, we identified the most important indicators (shown in Fig. 5-4). For example, we choose to focus on electricity consumption for energy consumption, and consider CO2 emission for polluting emissions. The definition of “scarce material” is adopted from the list of “critical raw materials” defined by European commission (The ad-hoc Working Group, 2010). The final waste is not considered in ASIT-E, mainly because it can be covered by material recoverability and the use

of hazardous materials; the recoverability is inversely proportional to the final waste, and if no hazardous material is used, the final waste is not going to be hazardous either. The indicators used in ASIT-E are customizable.

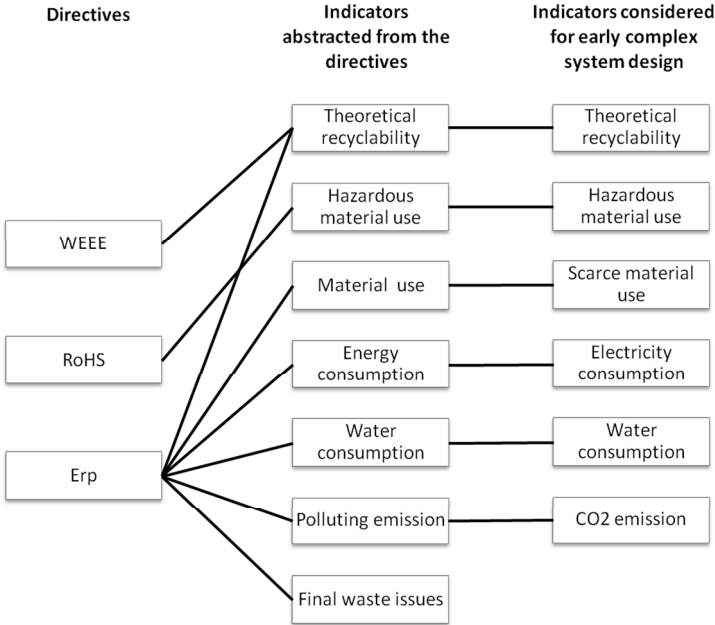


Figure 5-4 Indicator identification from directives

We regroup the indicators related to architectures and suppliers into three categories (shown in Fig. 5-5) in order to use them in different steps within ASIT-E. The first group of indicators relates to modules, while the second group relates to environmental capability of suppliers. The third group of indicators relates to both architectures and suppliers and the entire lifecycle of the product. For example, the electricity consumption can occur during production, transportation, product use, and disposal. In ASIT-E, we use the first and second group of indicators to filter out modules and suppliers, in order to avoid unqualified candidates; then, use the remaining modules to generate architectures. Finally, indicators from the third group are estimated for the entire lifecycle for each product architecture.

Module related	Supplier related	Architecture related
M1 Theoretical recyclability	S1 ISO 14001	A1 Electricity consumption
M2 Hazardous material use	S2 Environmental friendly packaging	A1 Water consumption
M3 Scarce material use	S3 Use of recycled material	A1 CO2 emission
	S4 Public disclosure of environmental record	

Figure 5-5 Environmental indicators used in ASIT-E

5.3 Environmental impact estimation in system architecture and supplier identification: proposition of ASIT-E

The work of Hallstedt, Ny, Robèrt, & Broman (2010) indicates that suitable decision support tools are needed for companies to successfully integrate environmental benefits into their business goals and plans. Lamming & Hampson (1996) also affirm that there is a need to develop practical solutions to meet environmental challenges. In this section, we propose such a decision support tool for OEMs to assist their environmental impact estimation during architecture and supplier identification.

The ASIT-E is an enhanced version of ASIT (Architecture & Supplier Identification Tool) proposed by Ye, Jankovic, Kremer, & Bocquet (2014). ASIT-E adds consideration of environmental issues to better satisfy the needs of OEMs. As shown in Fig. 5-6, ASIT-E starts from estimation of new requirements satisfaction by existing products; identifies requirements that are not satisfied; and finds new modules (possibly from new suppliers) that can potentially better satisfy the requirements. The potential modules set is filtered by the module and supplier related environmental indicators in order to weed out the inadequate modules and suppliers. All possible architectures are then regenerated using qualified modules. Then, the requirements satisfaction and uncertainty of architectures are estimated; architectures are filtered by requirements satisfaction and uncertainty thresholds. Finally, the environmental impact of the remaining architectures is estimated; and the environmental impact threshold is used to filter the architectures once again. A list of qualified architectures and suppliers is generated as candidates for further negotiation. The ASIT-E steps (listed on the left side of Fig. 5-6) are automated by a MatLab program. The steps highlighted with a dark background are specific to ASIT-E (not included in ASIT).

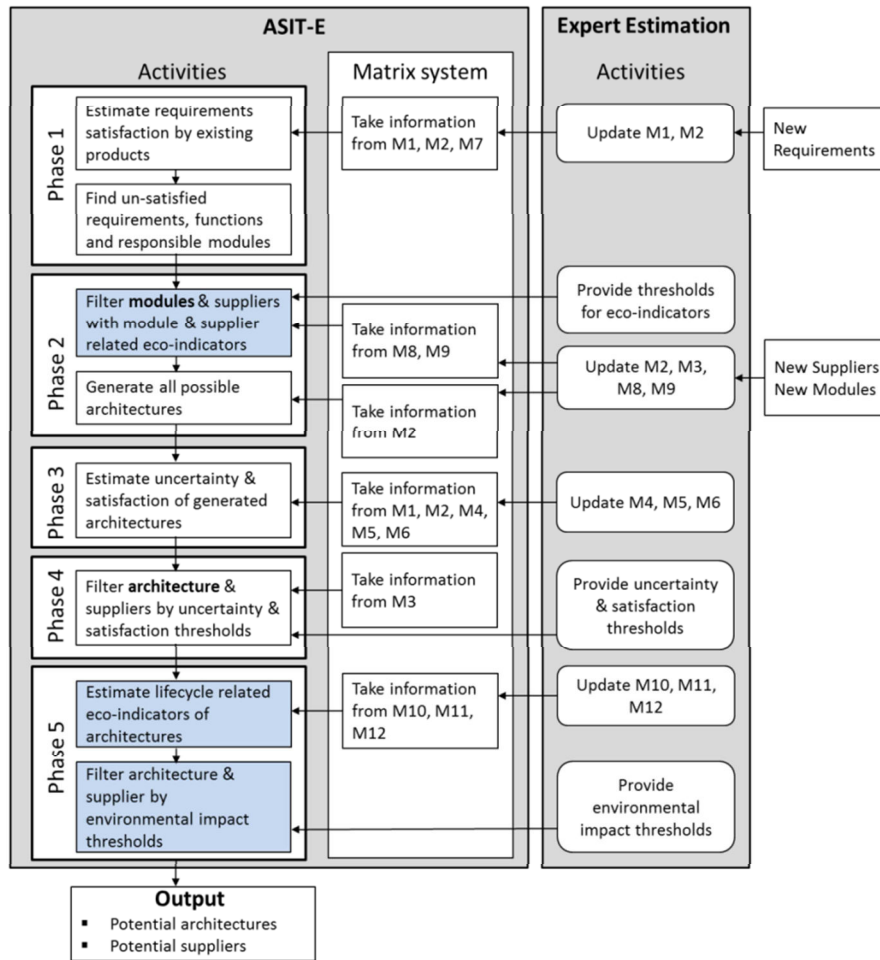


Figure 5-6 Overview of ASIT-E

ASIT-E uses a matrix system (shown in Fig. 5-7) as database. Due to uncertainty management, complex systems are rarely designed from scratch. Project documents regarding requirements, functions, and modules usually exist. Normally, this information is captured and reused using software such as DOORS. However, different types of data are rarely stored in one place. The idea behind ASIT and ASIT-E databases is to store critical, high-level data from previous projects within one matrix system, to facilitate information organization, acquisition, and utilization.

ASIT has seven matrices in its matrix system: matrices 1, 2, and 3, represent requirements, function, module relations; matrices 4, 5 and 6 represent uncertainty information: the compatibility between modules (4), uncertainty of modules (5), and uncertainty of suppliers' capabilities (7). Matrix 7 represents composition of existing products. In addition to these seven matrices, ASIT-E has five more matrices (8-12). Matrices 8 and 9 represent module related and supplier related environmental indicators, respectively; while matrices 10, 11, and 12 represent architectures' performance in lifecycle related environmental indicators (i.e., electricity consumption, water consumption, and CO2 emission).

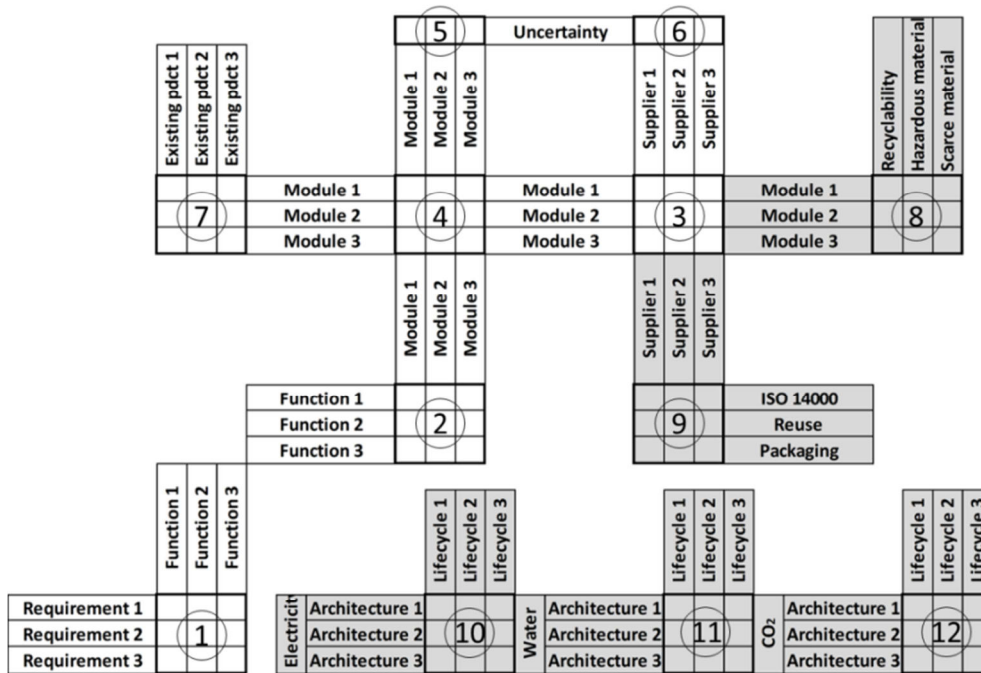


Figure 5-7 Matrix system used in ASIT-E

When starting a new project, usually the project manager organizes a 1-3 day workshop to discuss innovation integration, different system architectures, as well as other constrains. These workshops are attended by experts of different domains in order to cover overall system knowledge. The ASIT-E is conceived for use during this kind of a workshop, and the matrix system can be filled in part by the group of experts attending the workshop, and by data from existing products as well as information provided by suppliers. When filling the matrix system, experts use predefined linguistic terms of satisfaction levels and probabilities as shown in Fig.5-8 and Fig. 5-9. When estimating satisfaction levels, “0” is used to represent that “the module does not provide the function”.

Linguistic terms	Satisfaction level
Very inadequate solution	1
Weak solution	2
Tolerable solution	3
Adequate solution	4
Satisfactory solution	5
Good solution with few drawbacks	6
Good solution	7
Very good solution	8
Solution better than requirements	9
Ideal solution	10

Figure 5-8 Satisfaction levels (Fiod-Neto& Back, 1994)

Linguistic terms	Probability
Impossible	0
Nearly impossible	0.1
Very unlikely	0.2
Quite unlikely	0.3
Possible	0.4
Even chance	0.5
Better than even chance	0.6
Quite likely	0.7
Very likely	0.8
Nearly certain	0.9
Certain	1

Figure 5-9 Probabilities

In the next section, a powertrain design case is used to illustrate the utilization of ASIT-E.

5.4 The Powertrain Design Case

5.4.1 Case description

We use the design of a plug-in hybrid electric powertrain to show utilization of ASIT-E. A powertrain is a system of mechanical parts in a vehicle that first provides energy, and then converts it in order to propel the vehicle. The main objective in designing a powertrain is to provide adequate propulsion with minimal use of fuel while emitting minimal hazardous by-products or pollutants.

This case study involves three types of powertrains: the traditional gas powertrain, the hybrid electric powertrain, and the plug-in electric powertrain. In a traditional gas powertrain, the engine provides power converting from other sources of energy (e.g., gasoline). The transmission then takes the power, or output, of the engine and, through specific gear ratios, slows it and transmits it as torque. Through the driveshaft, the engine's torque is transmitted to the final drive (wheels, continuous track, etc.) of the car. A conventional hybrid electric powertrain utilizes both a combustion engine and an electric motor to provide power. The batteries are used to store electrical energy. The plug-in hybrid electric powertrain is the powertrain that utilizes rechargeable batteries that can be restored to full-charge by connecting to an external electric power source (such as a normal electric wall socket). The plug-in hybrid electric powertrain has great potential to reduce greenhouse gas emissions, since it uses no fuel during its all-electric range; normally, the combustion engine works only when the batteries are depleted. An example of the plug-in hybrid electric powertrain is shown in Fig.5-10.



Figure 5-10 Toyota Prius Plug-in Hybrid Electric Powertrain (Beissmann, 2011)

Due to the increasing demand of higher fuel efficiency and lower CO₂ emission, the OEM plans to design a new plug-in hybrid electric powertrain for their motor vehicle to better satisfy market needs. The new powertrain needs to satisfy mainly six requirements (requirements 1-4 are adapted from Michelen & Papalambros, (1995)): (1) Corporate Average Fuel Economy (CAFE) standard: Europe currently requires 54 miles per UK gallon, violation of this standard results in proportional fines, (2) Acceleration time: This directly relates to customer perceived performance, (3) Cruising velocity at gradient: Relates to the speed at which vehicle can climb a 6% gradient in forth gear, (4) Greenhouse gas emissions: This measure shows a vehicle's impact on climate change in terms of the amount of greenhouse gases (e.g., CO₂) it emits. (5) Rechargeable by external electric power, and (6) Long All-Electric Range (AER): This indicates the driving range of the vehicle using only power from its electric battery pack, in charge-depleting mode.

The powertrain design case used in this paper is similar to the one used in our previous work (Ye et al., 2014). Here, the case study focuses specifically on the environmental impact estimation.

5.4.2 Phase I – Requirements satisfaction by existing products

Complex systems are rarely designed from scratch. OEMs usually try to improve their existing products to satisfy new requirements. However, it is usually not clear which module should be improved and for which function of the module. In ASIT, we proposed to first estimate how well OEM's existing products satisfy the new requirements. By using matrix mapping, the unsatisfied requirements can be traced to unsatisfied functions, and finally to responsible modules. Thereby, OEMs know exactly which modules and functions to improve.

With support of the matrix system, experts can choose adequate existing requirements from the list; and if necessary, add new requirements to it. Based on the requirement-function relations stored in matrix M1, the existing functions related to defined requirements can be found. The requirements – function relations for new requirements are provided by experts using percentages (representing the contribution of a function to a requirement), as shown in Fig.5-11. Experts only need to fill out the white area of the matrix, because the other information is filled automatically using information from existing products.

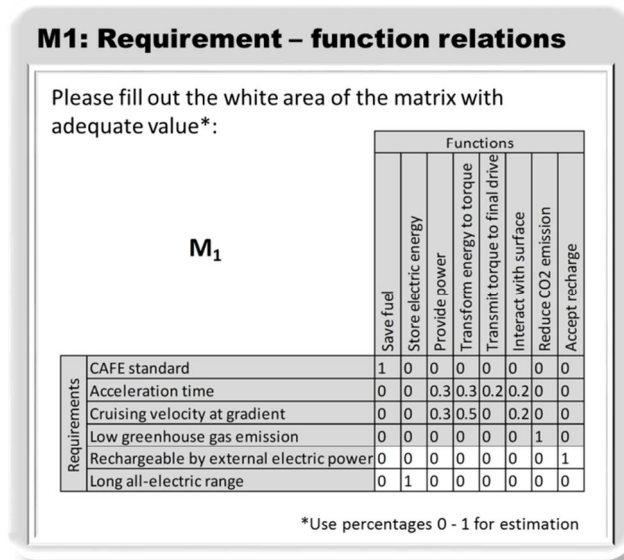


Figure 5-11 Requirement – function relations

Experts also discuss module types that are needed based on functions, and relations between new functions and module types. How well each module satisfies the new functions is also provided by experts, using satisfaction levels, as shown in Fig.5-12.

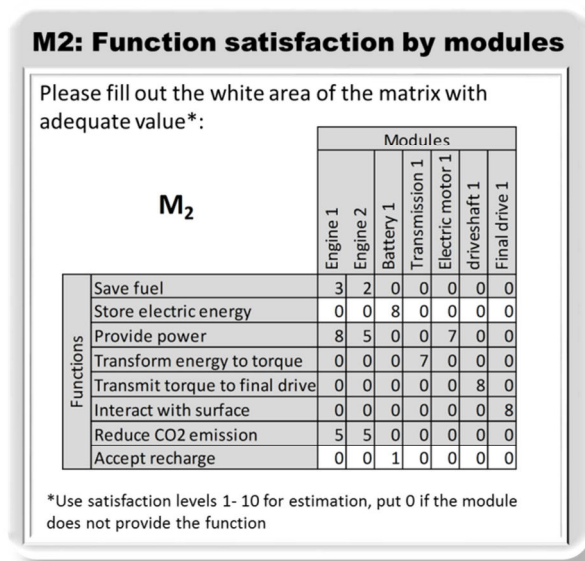


Figure 5-12 Function satisfaction level by modules

The OEM has successfully developed two types of powertrains in the past (i.e., a traditional gas powertrain, and a hybrid electric powertrain), which are used as foundations for the new powertrain development. M7 (Fig.5-13) shows the composition of the two powertrains. We assume that this information is already stored in the database, as it is updated after each project.

M₇

		Gas powertrain	Hybrid powertrain
Modules	Engine 1	1	0
	Engine 2	0	1
	Battery 1	0	1
	Transmission 1	1	1
	Electric motor 1	0	1
	Driveshaft 1	1	1
	Final drive 1	1	1

Figure 5-13 Composition of existing powertrains

By using M1, M2, and M7, ASIT-E can calculate how well the existing products satisfy the requirements. ASIT-E converts “how module satisfies functions (in M2)” to “how an existing product satisfies functions” using product composition in M7. The satisfaction of a function by a product is defined as the average of satisfaction levels of the modules in the product that are designed to fulfil the function. For example, the hybrid powertrain has two modules (engine 2 and electric motor 1) fulfilling the function “provide power”. Therefore, if the “engine 1” satisfies the “provide power” function at level 5 and “electric motor 1” satisfies the function at level 7, then the gas powertrain satisfies this function at level 6 (average of 5 and 7), as shown in matrix M_{fun-arch} in Fig.5-14.

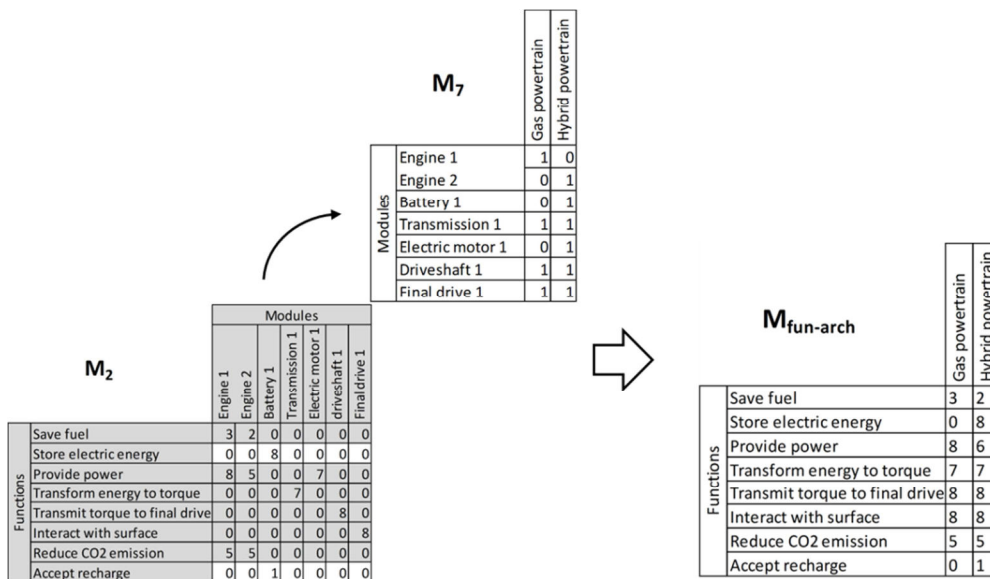


Figure 5-14 Function satisfaction level by existing products

Then, the requirement – function relations (M1) are used to propagate the satisfaction of functions to the satisfaction of requirements using the formula:

$$M_{req-arch} = M_1 \times M_{fun-arch}$$

The requirements satisfaction of existing powertrains is shown in Figure 5-15.

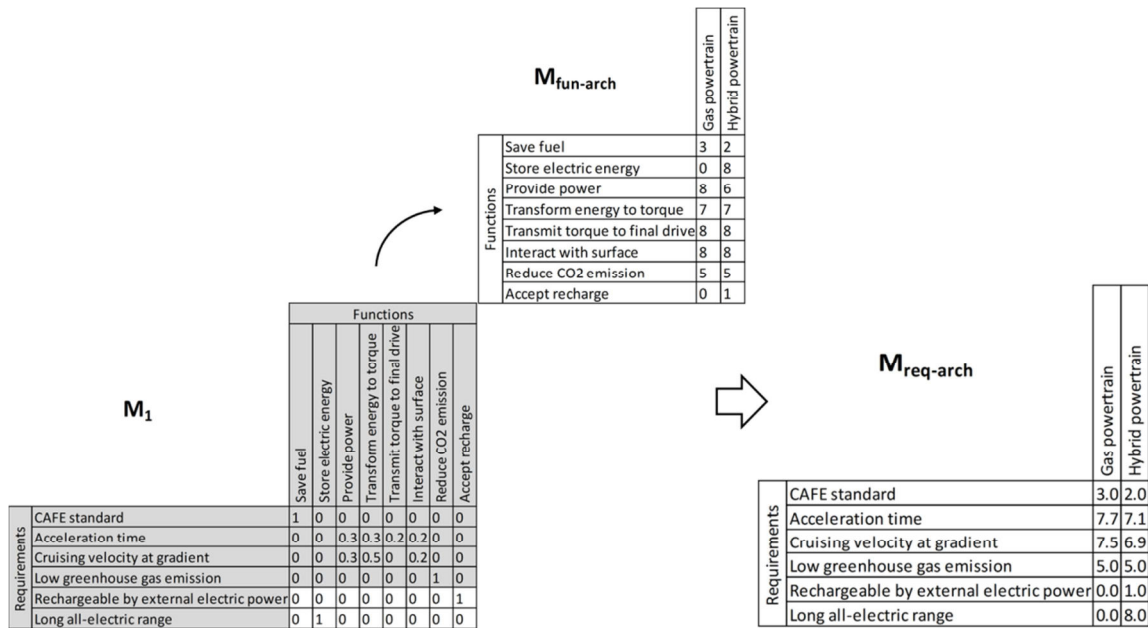


Figure 5-15 Requirement satisfaction of existing products

Since level 5 is defined as the default “satisfactory solution” (which can be changed if necessary), the requirements “CAFE standard”, “rechargeable by external electric power”, and “long all-electric range” are unsatisfied. Shown in Fig. 5-16, the requirement “CAFE standard” is related to the function “save fuel”, the requirement “rechargeable by external electric power” is related to the function “accept recharge”, and the requirement “long all-electric range” is related to the function “store electric energy”. Using M₂, it can be seen that the satisfaction of these three functions depends only on the engine and the battery. Therefore, new engines and batteries, which can potentially satisfy these functions, need to be developed.

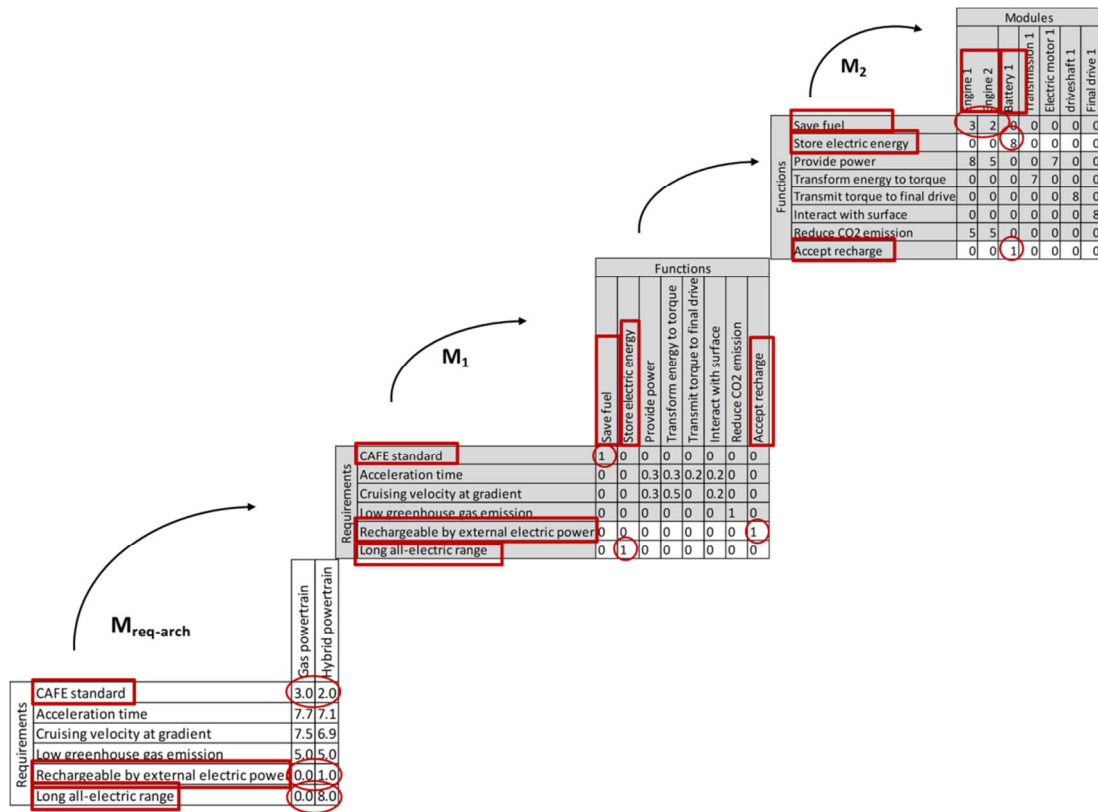


Figure 5-16 Matrix mapping for finding responsible modules

5.4.3 Phase II– Module, supplier filtering & solution generation

The objective of this phase is to (1) find/propose potential new solutions by experts for unsatisfied functions, (2) use module related environmental indicators (theoretical recyclability, hazardous material use, and scarce material use) and supplier related environmental indicators (ISO 14001, environmental friendly packaging, use of recycled material, and public disclosure of environmental record) to filter solutions, and (3) generate all possible architectures with integration of the new modules that meet the standards.

After searching for new modules provided either by new or existing suppliers, four new engines (engine #3, #4, #5, and #6) and five new batteries (batteries #2, #3, #4, #5, and #6) are found. The simplified descriptions of these modules are shown in Fig. 5-17.

Supplier	Module	Main Material	Fuel (for engine)
#1	Engine 1	Steel	Diesel
#1	Engine 2	Steel	Gasoline
#1	Engine 3	Aluminum	Gasoline
#2	Engine 4	Steel	Hydrogen
#3	Engine 5	Steel	Hydrogen
#4	Engine 6	Steel	CNG (Compressed Nature Gas)
#5	Battery 1	NiMH (Nickel Metal Hybride)	
#6	Battery 2	LiFePO ₄	
#6	Battery 3	Lithium-ion	
#7	Battery 4	Lithium-ion	
#7	Battery 5	Nickel-Cadmium	
#8	Battery 6	Carbon Nanotube Electrode Lithium	

Figure 5-17 Engines and Batteries

The module-related indicators and supplier-related indicators are used to control the environmental impact of these modules and their suppliers, before integrating these modules into architectures. Ideally, the estimation of these two types of indicators is based on information provided by suppliers. However, the quality of information provided by suppliers varies a lot. Therefore, if the information from suppliers is not complete, OEMs can rely on expert estimation. In the worst case, if experts are not able to provide estimations of a certain indicator, OEM can consider other indicators. Sometimes, for the same indicator, different OEMs may have different interpretations. For example, for “environmental friendly packaging”, OEM can consider the recyclability of packaging material, or the mass of packing material per mass of the module. In this work, we focus on illustrating the overall implementation of the ASIT-E structure, rather than proposing a detailed estimation method for each indicator. The estimations of module-related and supplier-related environmental indicators are shown in Fig. 5-18 and Fig. 5-19, respectively.

M8: Module related environmental indicators

Please fill out the white area of the matrix with adequate value:

		Module related environmental indicators		
		Hazardous material use	Theoretical recyclability	Scarce material use
		The module's propability of satisfying RoHS (Probability: 0-1)	Theoretical material recycling rate (by weight) (Percentage: 0-1)	Consider scarcity and quantity of scarce material (Satisfaction: 1-10)
Supplier	Module			
#1	Engine 1	0.9	0.9	7
#1	Engine 2	0.9	0.9	7
#1	Engine 3	0.9	0.9	4
#2	Engine 4	0.9	0.9	7
#3	Engine 5	0.9	0.9	7
#4	Engine 6	0.9	0.9	7
#5	Battery 1	0.8	0.8	4
#6	Battery 2	0.8	0.7	6
#6	Battery 3	0.8	0.7	6
#7	Battery 4	0.8	0.7	6
#7	Battery 5	0.1	0.6	6
#8	Battery 6	0.8	0.7	6

Figure 5-18 Estimation of module related environmental indicators

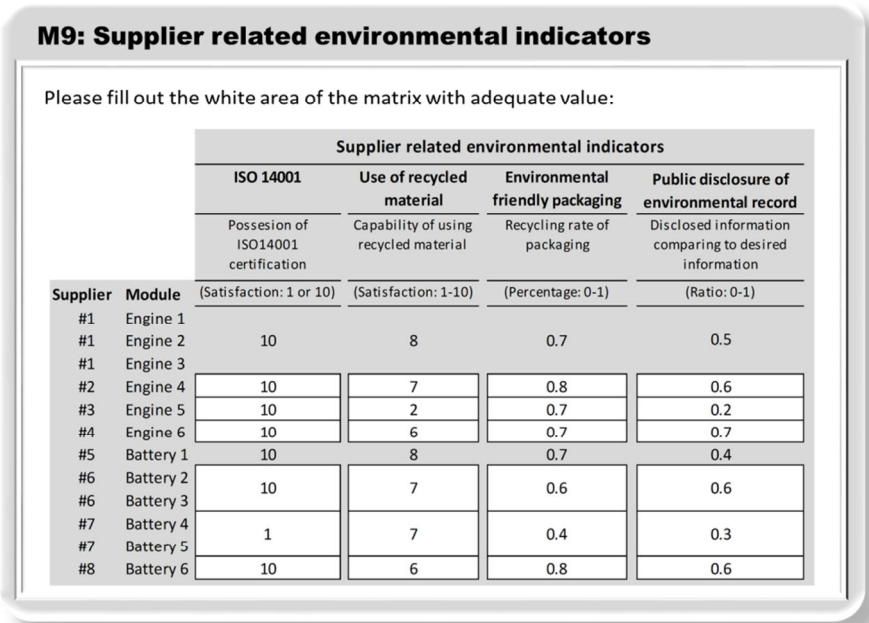


Figure 5-19 Estimation of supplier related environmental indicators

In order to filter the modules and suppliers, experts are asked to provide thresholds for environmental indicators (see Fig. 5-20). The thresholds for some of the indicators come from environmental directives (e.g., hazardous material use and theoretical material recyclability). For others, the threshold setting is for the purpose of getting an appropriate number of candidates when exploring the design space, and can be one of the decision parameters for experts.

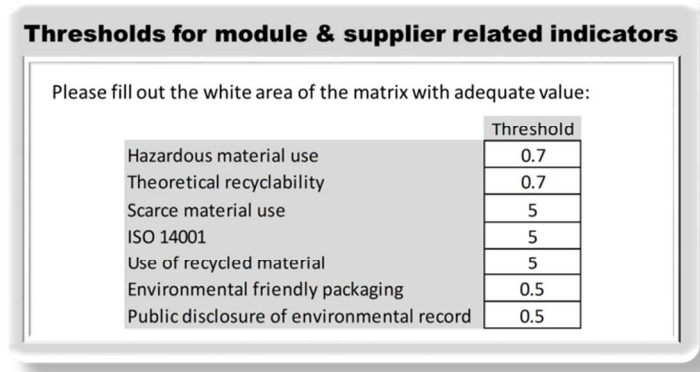


Figure 5-20 Thresholds for module & supplier related indicators

Using the thresholds provided, we can see that (in Fig. 5-21) engines 3 and 5 and batteries 1 and 5 are weeded out; and the suppliers 3, 5, and 7 are eliminated. However, since the supplier 7 provides battery 4 also, the battery 4 should be weeded out because of the unsatisfactory performance of its supplier.

Module	Module related environmental indicators			Supplier related environmental indicators			
	Hazardous material use	Theoretical recyclability	Scarce material use	ISO 14001	Use of recycled material	Environmental friendly packaging	Public disclosure of environmental record
	(Probability: 0-1)	(Percentage: 0-1)	(Satisfaction: 1-10)	(Satisfaction: 1 or 10)	(Satisfaction: 1-10)	(Percentage: 0-1)	(Ratio: 0-1)
	0.7	0.7	5	5	5	0.5	0.5
Module				Supplier			
Engine 1	0.9	0.9	7				
Engine 2	0.9	0.9	7	#1	10	8	0.7
Engine 3	0.9	0.9	4				
Engine 4	0.9	0.9	7	#2	10	7	0.8
Engine 5	0.9	0.9	7	#3	10	2	0.7
Engine 6	0.9	0.9	7	#4	10	6	0.7
Battery 1	0.8	0.8	4	#5	10	8	0.7
Battery 2	0.8	0.7	6	#6	10	7	0.6
Battery 3	0.8	0.7	6				
Battery 4	0.8	0.7	6				
Battery 5	0.1	0.6	6	#7	1	7	0.4
Battery 6	0.8	0.7	6	#8	10	6	0.8

Figure 5-21 Filtering using module and supplier related indicators

When estimating environmental performance, battery 5 (Nickel-Cadmium Battery) received a very low score for “Hazardous material use” since one of the core material in this battery is Cadmium, which is toxic. For scarce material use, Engine 3 received a low score because of the utilization of Aluminum. Battery 1 (NiMH) uses approximately 4.5 kg of rare earth metals, while the Li-based batteries contain only about 1 kg of rare earths (Ford, 2012). The supplier 5 does not have an effective reverse logistic system, and the supplier 7 does not have ISO 14001 certification.

After filtering, new modules that were found appropriate are added into database, and the matrix M2 is updated by experts (shown in Fig.5-22).

M2: Function satisfaction by modules

Please fill out the white area of the matrix with adequate value*:

Functions	Modules										
	Engine 1	Engine 2	Engine 4	Engine 6	Battery 2	Battery 3	Battery 6	Transmission 1	Electric motor 1	driveshaft 1	Final drive 1
Save fuel	3	2	10	7	0	0	0	0	0	0	0
Store electric energy	0	0	0	0	7	5	10	0	0	0	0
Provide power	8	5	5	7	0	0	0	0	7	0	0
Transform energy to torque	0	0	0	0	0	0	0	7	0	0	0
Transmit torque to final drive	0	0	0	0	0	0	0	0	0	8	0
Interact with surface	0	0	0	0	0	0	0	0	0	0	8
Reduce CO2 emission	5	5	10	8	0	0	0	0	0	0	0
Accept recharge	0	0	0	0	8	8	9	0	0	0	0

*Use satisfaction levels 1- 10 for estimation, put 0 if the module does not provide the function

Figure 5-22 Function – module relations with new modules

The relations between modules and suppliers are also provided by experts, indicating which module is provided by which supplier.

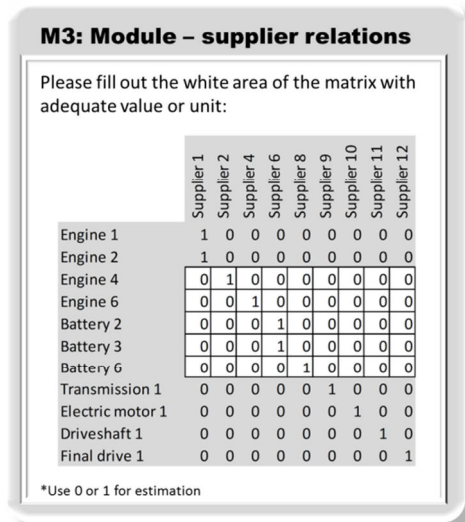


Figure 5-23 M3: module – supplier relations

Based on modules shown in M2 in Fig.5-22, all possible architectures are generated (Fig.5-24) by taking one module from each module type, since the powertrain of a plug-in hybrid electric vehicle is composed of an engine, a battery, a transmission, an electric motor, a driveshaft and a final drive.

		Possible architecture 7	Possible architecture 8	Possible architecture 10	Possible architecture 12	Possible architecture 13	Possible architecture 14	Possible architecture 16	Possible architecture 18	Possible architecture 31	Possible architecture 32	Possible architecture 34	Possible architecture 36
Modules	Engine 1	1	0	0	0	1	0	0	0	1	0	0	0
	Engine 2	0	1	0	0	0	1	0	0	0	1	0	0
	Engine 4	0	0	1	0	0	0	1	0	0	0	1	0
	Engine 6	0	0	0	1	0	0	0	1	0	0	0	1
	Battery 2	1	1	1	1	0	0	0	0	0	0	0	0
	Battery 3	0	0	0	0	1	1	1	1	0	0	0	0
	Battery 6	0	0	0	0	0	0	0	0	1	1	1	1
	Transmission 1	1	1	1	1	1	1	1	1	1	1	1	1
	Electric motor 1	1	1	1	1	1	1	1	1	1	1	1	1
	Driveshaft 1	1	1	1	1	1	1	1	1	1	1	1	1
	Final drive 1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5-24 Generated possible architectures

5.4.4 Phase III– Evaluating uncertainty & requirements satisfaction

The objective of this phase is to calculate uncertainty and requirements satisfaction of all possible architectures. Three types of uncertainty are considered when calculating the overall uncertainty of an architecture: (1) interface compatibilities between modules due to innovation integration, (2) the uncertainty of modules (representing the probability that the module can be developed successfully by suppliers), and (3) the probability that a supplier and the OEM can work well together. ASIT-E is based on expert estimation for these three types of uncertainty, shown in Fig. 5-25, Fig. 5-26, and Fig. 5-27.

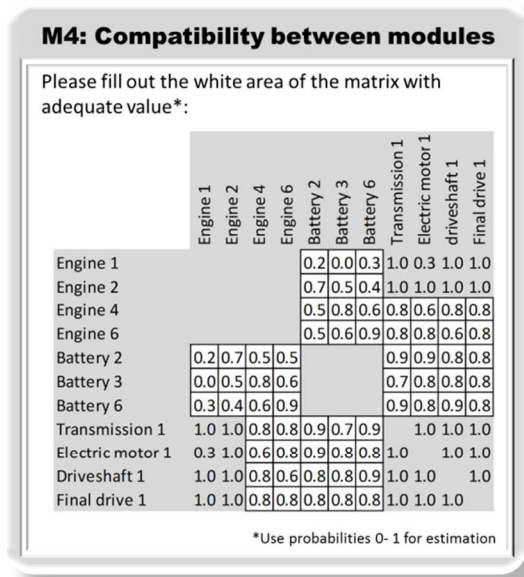


Figure 5-25 Expert estimation of compatibility between modules

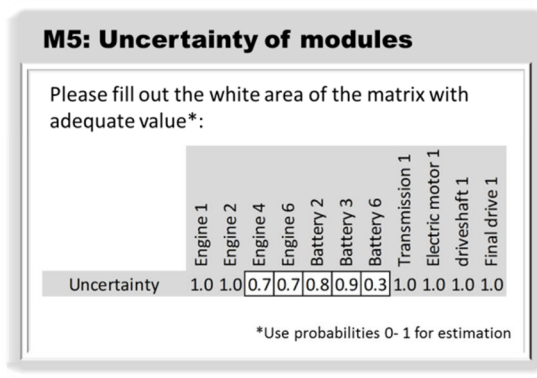


Figure 5-26 Expert estimation of module uncertainty

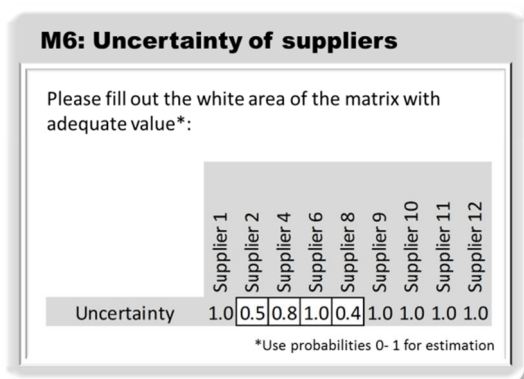


Figure 5-27 Expert estimation of supplier uncertainty

Since module uncertainty (the probability that the module can be developed successfully), supplier uncertainty (the probability that the OEM and the supplier can work well together) and compatibility between modules can all be considered in probabilistic terms, we define the uncertainty of an architecture as the product of all its modules' uncertainties, its suppliers' uncertainties and the compatibilities between the modules. This definition anchors on the independence of probabilities.

Done in a similar way as in calculating the requirements satisfaction by existing products, the requirements satisfaction by possible architectures is calculated using the matrix M2 (in Figure 5-22) and the matrix M1 (in Figure 5-11). In this case, we assume equal importance of the requirements (this assumption can be changed if needed), an overall requirements satisfaction score is obtained for each of the possible architectures by calculating the average of all requirements satisfaction scores for the architecture.

The obtained uncertainties and satisfaction levels are presented in Figure 5-28. The “overall uncertainty” represents the overall confidence level of an architecture. Bigger the overall uncertainty is greater the level of confidence we have for the architecture. The “requirement satisfaction” represents the satisfaction level of the requirements by an architecture. Bigger it is, better the architecture satisfies the requirements.

Architecture	7	8	10	12	13	14	16	18	31	32	34	36
Overall uncertainty	0.02	0.29	0.02	0.04	0.00	0.16	0.02	0.03	0.01	0.02	0.00	0.01
Requirement satisfaction	6.3	6.0	8.2	7.4	6.0	5.7	7.8	7.1	7.0	6.7	8.8	8.1

Figure 5-28 Uncertainty and requirements satisfaction for possible architectures

5.4.5 Phase IV– Uncertainty & requirements satisfaction filtering

The aim of this phase is to filter possible architectures by their uncertainties and requirement satisfaction levels.

By asking experts to define uncertainty and satisfaction thresholds, ASIT-E can filter architectures in order to keep architectures with best performances while rejecting highly uncertain ones.

In order to obtain an adequate number of candidates, the uncertainty threshold is set to 0.02, and the satisfaction threshold is set to 6.5. All architectures with uncertainty lower than 0.02 and satisfaction level lower than 6.5 are eliminated. After filtering, only 5 out of the 12 generated architectures remain (architectures 10, 12, 16, 18, 32), as shown in Fig. 5-29, for final consideration. By using matrix mapping, it can be seen that engine 1 is filtered out.

Overall uncertainty	0.02	0.29	0.02	0.04	0.00	0.16	0.02	0.03	0.01	0.02	0.00	0.01
Requirement satisfaction	6.3	6.0	8.2	7.4	6.0	5.7	7.8	7.1	7.0	6.7	8.8	8.1
Possible architecture 7	1	0	0	0	1	0	0	0	1	0	0	0
Possible architecture 8	0	1	0	0	0	1	0	0	0	1	0	0
Possible architecture 10	0	0	1	0	0	0	1	0	0	0	1	0
Possible architecture 12	0	0	0	1	0	0	0	1	0	0	0	1
Possible architecture 13	1	1	1	1	0	0	0	0	0	0	0	0
Possible architecture 14	0	0	0	0	1	1	1	1	0	0	0	0
Possible architecture 16	0	0	0	0	0	0	0	0	1	1	1	1
Possible architecture 18	1	1	1	1	1	1	1	1	1	1	1	1
Possible architecture 31	1	1	1	1	1	1	1	1	1	1	1	1
Possible architecture 32	1	1	1	1	1	1	1	1	1	1	1	1
Possible architecture 34	1	1	1	1	1	1	1	1	1	1	1	1
Possible architecture 36	1	1	1	1	1	1	1	1	1	1	1	1
Supplier 1	1	0	0	0	0	0	0	0	0	0	0	0
Supplier 2	1	0	0	0	0	0	0	0	0	0	0	0
Supplier 4	0	1	0	0	0	0	0	0	0	0	0	0
Supplier 6	0	0	1	0	0	0	0	0	0	0	0	0
Supplier 8	0	0	0	1	0	0	0	0	0	0	0	0
Supplier 9	0	0	0	0	1	0	0	0	0	0	0	0
Supplier 10	0	0	0	0	0	1	0	0	0	0	0	0
Supplier 11	0	0	0	0	0	0	1	0	0	0	0	0
Supplier 12	0	0	0	0	0	0	0	1	0	0	0	0
Engine 1	1	0	0	0	0	0	0	0	0	0	0	0
Engine 2	1	0	0	0	0	0	0	0	0	0	0	0
Engine 4	0	1	0	0	0	0	0	0	0	0	0	0
Engine 6	0	0	1	0	0	0	0	0	0	0	0	0
Battery 2	0	0	0	1	0	0	0	0	0	0	0	0
Battery 3	0	0	0	0	1	0	0	0	0	0	0	0
Battery 6	0	0	0	0	0	1	0	0	0	0	0	0
Transmission 1	0	0	0	0	0	0	1	0	0	0	0	0
Electric motor 1	0	0	0	0	0	0	0	1	0	0	0	0
Driveshaft 1	0	0	0	0	0	0	0	0	1	0	0	0
Final drive 1	0	0	0	0	0	0	0	0	0	1	0	0

Figure 5-29 Uncertainty and satisfaction filtering of possible architectures

5.4.6 Phase V– Estimating architecture related indicators & filtering

The objective of this phase is to filter remaining architectures using their performances in electricity consumption, water consumption and CO2 emission. The reason that this step is not done in parallel with uncertainty and requirements satisfaction filtering is that the estimation of these three environmental indicators require relatively more information and processing. Therefore, it is necessary to reduce the number of architectures first by uncertainty and requirements satisfaction thresholds.

The electricity consumption, water consumption and CO2 emission during the entire life time of an architecture depend on a lot of factors, and are difficult to estimate. Therefore at the conceptual stage of engineering design, we can only expect to have a rough idea about these three factors in order to compare options. Although “the entire life time of an architecture” is considered, it is neither efficient nor possible to consider all lifecycle phases for each indicator. Therefore, we consider only the most important phases for each indicator.

Another important factor to consider during estimation is the lifespan of each module. Because of our focus on the closed-loop supply chain, and according to WEEE, we consider that modules in an EOL system are collected and then re-used if they did not attain their lifespan. Therefore, if other characteristics of two modules are the same, but one has longer lifespan than another, we should consider that the module with longer lifespan is more environmentally friendly.

With the consideration of the most important lifecycle phases, and the lifespan of each module, the three indicators are calculated according to estimations provided by experts based on their experience, and information provided by suppliers. Finally, thresholds are used to filter architectures, to identify candidates.

5.4.6.1 Lifecycle phase selection, lifespan, and unit

Before estimation, ASIT-E asks experts to select the most important lifecycle phases for each indicator according to the type of system being designed (shown in Fig. 5-30). Normally, a phase is neglected if one of the criteria is satisfied:

- 1) The consumption or emission is negligible comparing to other phases;
- 2) The consumption or emission of the phase is similar for all possible architectures, therefore does not affect the comparison between architectures.

Important lifecycle phases for indicators

Please select the most important lifecycle phases for each indicator:

		Product Lifecycle Phases					
		Module production	Supplier - OEM transportation	Assembly	OEM - storage transportation	Storage	Utilization
Architecture Related Indicators	Product type: automobile powertrain						
	Electricity consumption	√					√
	Water consumption	√					
	CO2 emission	√	√				√
		Collection	Inspection & classification	Re-use (module)	Recycle (material)	Other recovery	Disposal
	Electricity consumption						
Water consumption				√		√	
CO2 emission							

Figure 5-30 Lifecycle phases selection for indicators

ASIT-E also asks for the estimation of a lifespan for each module and for the entire architecture (shown in Fig. 5-31). The units that will be used for estimation are also defined in order to facilitate further integration.

Lifespan & unit

Please fill the white area of the matrix with adequate lifespan or unit:

Lifespan estimation		Lifespan (year)
Architecture	Powertrain	12
	Engine 2	25
Module	Engine 4	35
	Engine 6	15
	Battery 2	10
	Battery 3	6
	Battery 6	12

Unit definition	Unit
Electricity consumption	TJ
Water consumption	kL
CO2 emission	t

Figure 5-31 Lifespan estimation & unit definition

In ASIT-E, we assume that the lifespan of the entire system under design (the powertrain in this case) is defined. This lifespan can be defined according to OEMs requirements on the system lifespan or according to market average. In this case study, we assume that the OEM wants the powertrain to last for about 12 years. The service unit of a powertrain is defined as “serve in a vehicle for 12 years”.

Using the lifespan of modules and system, the module depletion can be calculated, which represents the used up percentage of a module (e.g., engine) when serving a system (e.g., powertrain) (Fig. 5-32).

Module	Module Lifespan (year)	Module depletion per System
Engine 2	25	12/25 ~ 1/2
Engine 4	35	12/35 ~ 1/3
Engine 6	15	12/15 ~ 1
Battery 2	10	12/10 ~ 1
Battery 3	6	12/6 = 2
Battery 6	12	12/12 = 1

*System lifespan = 12 years

Figure 5-32 Module depletion per system

The module depletion is an approximation of quotient of system lifespan and module lifespan. When the module depletion is bigger than or equal to 1, it is approximated to the nearest integer; when it is between 0 and 1, it is approximated to a fraction whose denominator is an integer between 1 and 10.

In order to facilitate the value integration of different lifecycle phases, the estimation of the three indicators are provided using approximated quantitative values. The units of estimation are provided by experts based on data from previous projects.

5.4.6.2 Estimation of architecture related environmental indicators

The electricity consumption, water consumption, and CO2 emission are estimated by experts using predefined units. For the phase “utilization”, the environmental impact is considered for the entire lifespan of the system (12 years in this case).

M10: Electricity consumption

Please fill out the white area of the matrix with adequate value*:

Electricity Consumption					
Architecture	Core modules	Suppliers	Module depletion	Module production (TJ)	Utilization (TJ)
#10	Engine 4	#2	1/3	0.2	25
	Battery 2	#6	1	0.1	
#12	Engine 6	#4	1	0.1	25
	Battery 2	#6	1	0.1	
#16	Engine 4	#2	1/3	0.2	30
	Battery 3	#6	2	0.07	
#18	Engine 6	#4	1	0.1	30
	Battery 3	#6	2	0.07	
#32	Engine 2	#1	1/2	0.1	20
	Battery 6	#8	1	0.15	

*Use approximated quantitative for estimation

Figure 5-33 Experts’ estimation of electricity consumption

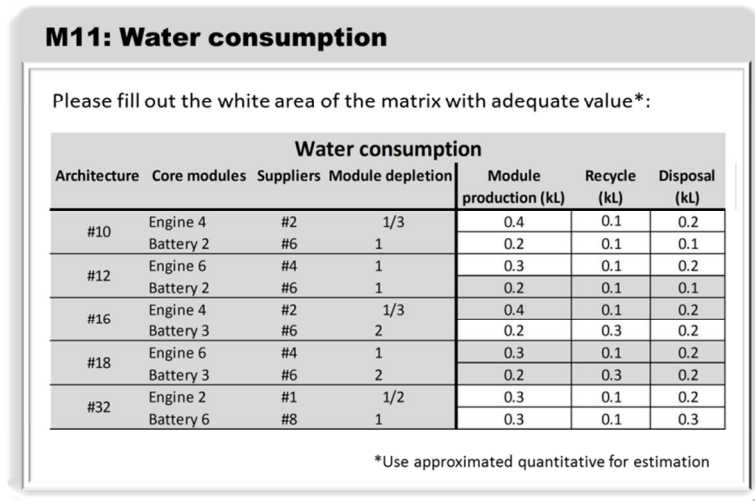


Figure 5-34 Experts' estimation of water consumption

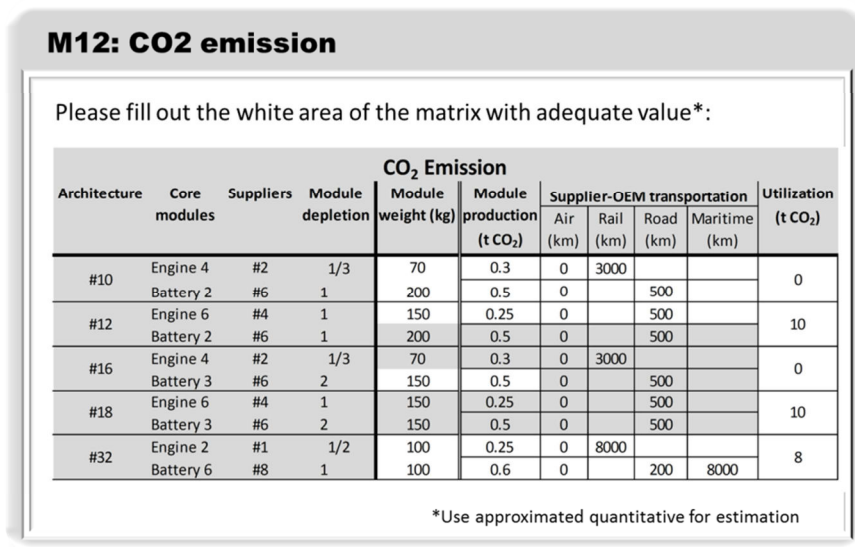


Figure 5-35 Experts' estimation of CO2 emission

The area with a grey background is filled in automatically by ASIT-E. For example, in Fig. 5-35, the CO₂ emission in module production for the same module is the same. Therefore, when experts estimated the CO₂ emission for manufacturing engine 4 in architecture 10, the CO₂ emission for producing engine 4 in architecture 16 can be filled by ASIT-E using the same value.

Different from other phases, the CO₂ emission of transportation is not estimated directly by experts due to its complexity. Instead, ASIT-E asks experts to provide estimation of module weight and transportation distance by different transportation means. For calculation of CO₂ emission, we use equation:

$$\text{CO}_2\text{emission} = \text{emission factor (depends on transportation mode)} \times \text{mass} \times \text{distance}$$

The emission factors is an average value that depends on transportation mode, and are adopted from ADEME (2010) as shown in Fig. 5-36.

Emission Factors (g CO ₂ /kg.km)				
	Air	Rail	Road	Maritime
Emission factor	0.61	0.062	0.074	0.15

Figure 5-36 Emission factors (adopted from ADEME (2010))

After calculation, the CO₂ emission estimates of architectures in different lifecycle phases are shown in Fig. 5-37.

Architecture	Core modules	Suppliers	Module depletion	Module production (t CO ₂)	Supplier-OEM transportation (t CO ₂)	Utilization (t CO ₂)
#10	Engine 4	#2	1/3	0.3	0.0013	0
	Battery 2	#6	1	0.5	0.0074	
#12	Engine 6	#4	1	0.25	0.0056	10
	Battery 2	#6	1	0.5	0.0074	
#16	Engine 4	#2	1/3	0.3	0.0013	0
	Battery 3	#6	2	0.5	0.0056	
#18	Engine 6	#4	1	0.25	0.0056	10
	Battery 3	#6	2	0.5	0.0056	
#32	Engine 2	#1	1/2	0.25	0.0050	8
	Battery 6	#8	1	0.6	0.1215	

Figure 5-37 Calculation of CO₂ emission for transportation

5.4.6.3 Calculation of environmental indicators & architecture filtering

Estimations of each indicator for each module/architecture are integrated to calculate the environmental performance of each possible powertrain regarding CO₂ emission, water consumption, and electricity consumption. The powertrains are then filtered to get the final architecture and supplier candidates.

We have seen that the powertrain is composed of six modules. Since in this case study, the transmission, electric motor, driveshaft, and final drive are the same for all architectural options, we consider only the two core modules (which are different from concept to concept) — engine and battery for comparison.

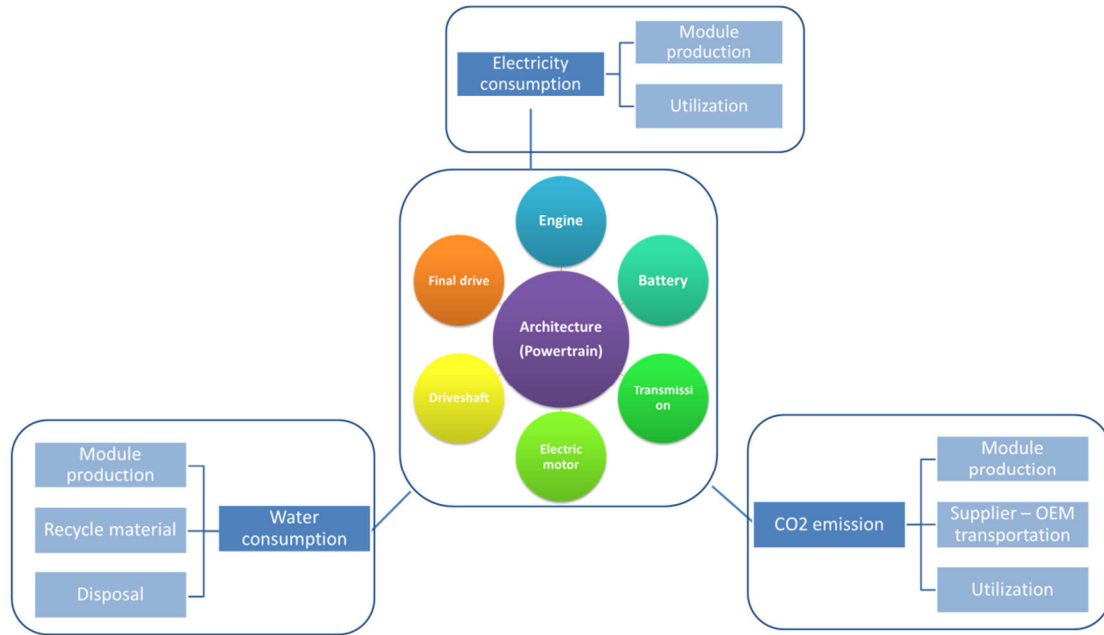


Figure 5-38 Integration of architecture related indicators

As a first step of integration, we calculate the electricity consumption, water consumption, and CO₂ emission for each powertrain concept separately, before integrating these three indicators for each concept during the second step. These three indicators are estimated for different lifecycle phases for the powertrain in the previous section. Therefore, it is sufficient to add consumption/emission of each phase up to get the overall value for the entire lifecycle, as estimates are quantitative. However, the lifespan of a module plays an important role in the calculation. For example, if two batteries are needed (one by one) for the lifecycle of powertrain, the pollution of producing the battery should be counted twice. Therefore, when adding the pollution of each lifecycle phase, a factor that is related to lifespan of each module should be considered for module related phases; we call this: “module depletion factor”, or “ f_n ”. The module depletion factor used here is shown in Fig. 5-39. The module depletion factor depends also on the type of architecture being considered.

Module Depletion Facotr (fn)

	Module depletion (n)		
	$n > 1$	$n = 1$	$n < 1$
	Lifecycle phases		
Module production	n	1	n
Supplier - OEM transportation	n	1	n
Assembly	1	1	1
OEM - storage transportation	1	1	1
Storage	1	1	1
Utilization	1	1	1
Collection	1	1	1
Inspection & classification	1	1	1
Re-use (module)	0	0	1- n
Recycle (material)	n	1	n
Other recovery	n	1	n
Disposal	n	1	n

Figure 5-39 Module depletion factor

Assume $n = 1/3$ (for engine #4 for example), which means that the engine #4 can serve 3 powertrains in its lifespan. Therefore, the module production and supplier-OEM transportation should be counted $1/3$ times in each powertrain lifecycle. From the lifecycle “assembly” to “inspection & classification”, the estimations are all based on the entire powertrain (e.g., the assembly is the assembly of the entire powertrain, not assembly of the module). Therefore, the lifespan of each module does not influence these lifecycle phases. If the module can be used in 3 powertrains, it can be re-used twice and recycled/recovered/disposed once. Therefore, for each powertrain lifecycle (12 years), the pollution of reuse should be counted $2/3$ times, and recycled/recovered/disposed should be counted $1/3$ times.

For the calculation of indicators, we use electricity consumption of architecture #10 as an example. Architecture #10 is composed of core modules engine #4 and battery #2. The important lifecycle phases are module production and utilization; therefore, it is sufficient to calculate electricity consumption of each important phase and then sum them up.

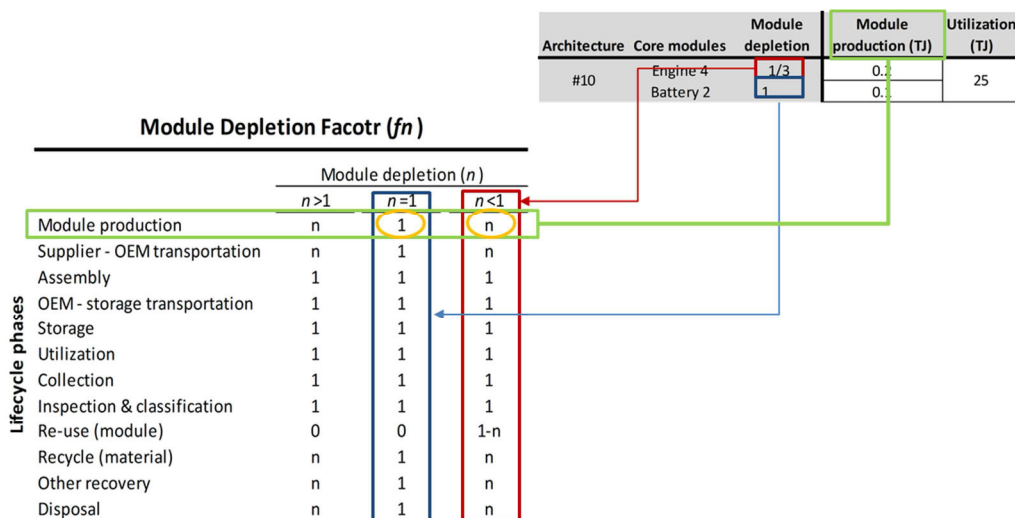


Figure 5-40 Integration

For the phase of module production, module depletion factor needs to be considered for the two modules:

Engine 4: Module depletion = $n = 1/3$

→ Module depletion factor for module production $fn(E4) = n = 1/3$

Battery 2: Module depletion = 1

→ Module depletion factor for module production $fn(B2) = 1$

Therefore, electricity consumption of module production of architecture 10 is:

$$\begin{aligned}
 &fn(E4) \times \text{Electricity consumption of producing E4} + fn(B2) \times \text{Electricity consumption of producing B2} \\
 &= \frac{1}{3} \times 0.2 + 1 \times 0.1 \\
 &= 0.17(TJ)
 \end{aligned}$$

The electricity consumption when using architecture 10 (for 12 years) is 25 TJ.

The electricity consumption of the entire cycle of architecture #10 is:

$$\begin{aligned}
 &\text{Electricity consumption of production} + \text{Electricity consumption of utilization} \\
 &= 0.17 + 25 \\
 &= 25.17(TJ)
 \end{aligned}$$

The water consumption and CO2 emission follow the same principle as electricity consumption. The environmental impact estimates for the three architecture related indicators are shown in Fig. 41.

Architecture	Supplier	Electricity consumption (TJ)	Water consumption (kL)	CO2 emission (t)
#10	#2,#6	25.17	0.67	0.61
#12	#4,#6	25.20	1.00	10.76
#16	#2,#6	30.21	1.07	1.11
#18	#4,#6	30.24	1.40	11.27
#32	#1,#8	20.20	1.00	8.85

Figure 5-41 Environmental impact calculation

In order to facilitate filtering, the values of the three indicators are normalized within each indicator category, by dividing the biggest value within the category, as shown in Figure 5-42.

Architecture	Supplier	Electricity consumption (TJ)	Water consumption (kL)	CO2 emission (t)
#10	#2,#6	0.83	0.48	0.05
#12	#4,#6	0.83	0.71	0.96
#16	#2,#6	1.00	0.76	0.10
#18	#4,#6	1.00	1.00	1.00
#32	#1,#8	0.67	0.71	0.79

Figure 5-42 Normalized environmental impact

Assuming equal importance of each indicator (this can be changed if necessary), the overall environmental impact of each architecture is calculated by adding the three indicators for each architecture. The result is then normalized through dividing by the biggest value. For normalized overall input, the smaller the value is, the less the environmental impact of the architecture becomes.

Architecture	Supplier	Overall environmental impact	Normalized overall impact
#10	#2,#6	1.37	0.46
#12	#4,#6	2.50	0.83
#16	#2,#6	1.86	0.62
#18	#4,#6	3.00	1.00
#32	#1,#8	2.17	0.72

Figure 5-43 Normalized overall environmental impact

Finally, experts can set a threshold for the normalized overall impact in order to filter the potential architecture set with a certain level of environmental impact.

The environmental threshold in this case set at 0.8; therefore, architectures with environmental impact bigger than 0.8 are eliminated. The architectures and suppliers, after filtering, are shown in Fig. 5-44, which are candidates for OEM’s further negotiation.

Architecture	Core modules	Module description	Suppliers
10	Engine 4 (new)	Steel, hydrogen	2 (new)
	Battery 2 (new)	LiFePO ₄	6 (new)
16	Engine 4 (new)	Steel, hydrogen	2 (new)
	Battery 3 (new)	Lithium-ion	6 (new)
32	Engine 2 (existing)	Steel, gasoline	1 (existing)
	Battery 6 (new)	Carbon nanotube electrode lithium	8 (new)

Figure 5-44 Identified potential architectures and suppliers

5.5 Comparison

In order to see how consideration of environmental issues influences the architecture and supplier identification results, we compare the result obtained by using ASIT-E to the result obtained using ASIT (where environmental issues are not considered) by using the same case study. Choosing to compare to ASIT is also because of the fact that there is currently no other similar method to ASIT-E.

Using ASIT, the modules shown in Fig. 5-17 are all used for generating possible architectures, without filtering by module related and supplier related environmental indicators. The generated possible architectures are shown in Fig. 5-45.

Modules	Possible architectures																																							
	Possible architecture 1	Possible architecture 2	Possible architecture 3	Possible architecture 4	Possible architecture 5	Possible architecture 6	Possible architecture 7	Possible architecture 8	Possible architecture 9	Possible architecture 10	Possible architecture 11	Possible architecture 12	Possible architecture 13	Possible architecture 14	Possible architecture 15	Possible architecture 16	Possible architecture 17	Possible architecture 18	Possible architecture 19	Possible architecture 20	Possible architecture 21	Possible architecture 22	Possible architecture 23	Possible architecture 24	Possible architecture 25	Possible architecture 26	Possible architecture 27	Possible architecture 28	Possible architecture 29	Possible architecture 30	Possible architecture 31	Possible architecture 32	Possible architecture 33	Possible architecture 34	Possible architecture 35	Possible architecture 36				
Engine 1	1	0	0	0	0	0	1	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	0	0	0	0		
Engine 2	0	1	0	0	0	0	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	0	1	0	0	0	0	
Engine 3	0	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	0	0	0	0	0	0	0	1	0	0	0	
Engine 4	0	0	0	1	0	0	0	0	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	0	1	0	0	0
Engine 5	0	0	0	0	1	0	0	0	0	0	1	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	0	0
Engine 6	0	0	0	0	0	1	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	0	0	0	0	1	0
Battery 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	0	0	0	0	0	0	0	0	0	0	0	0
Battery 2	0	0	0	0	0	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	0	0	0	0	0	0
Battery 3	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	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Battery 4	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	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Battery 5	0	0	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	1	1	1	1	1	1	1	1	1	1
Battery 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transmission 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	1	1	1	1	
Electric motor 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	1	1	1	1	
Driveshaft 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	1	1	1	1	
Final drive 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	1	1	1	1	

Figure 5-45 Generated possible architectures

Experts are asked to provide estimation on function satisfaction by modules, and module - supplier relations as shown in Fig. 5-46 and Fig. 5-47, respectively.

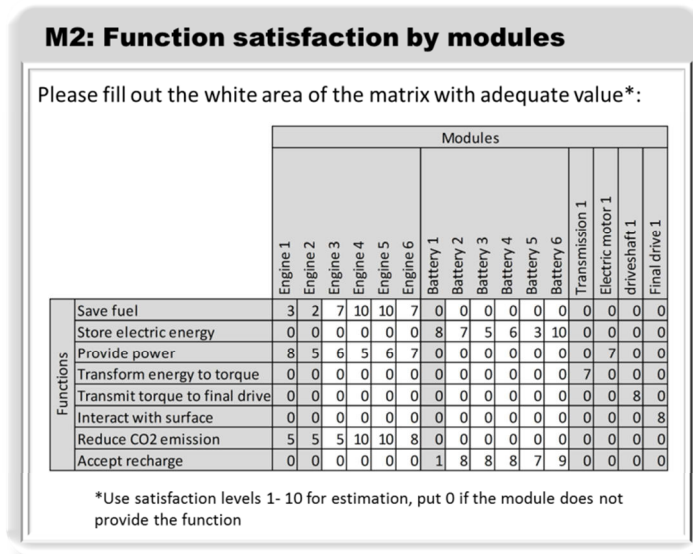


Figure 5-46 Function – module relations with new modules (ASIT)

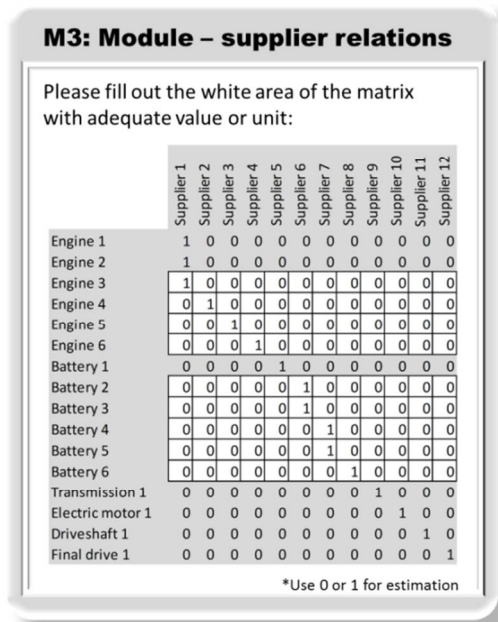


Figure 5-47 Module – supplier relations (ASIT)

The uncertainty information is also provided by experts as shown in Fig. 5-48, Fig. 5-49, and Fig. 5-50.

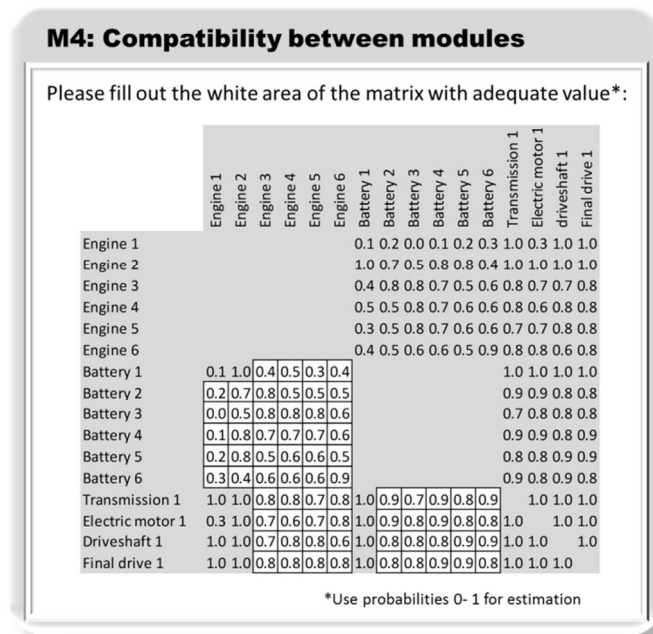


Figure 5-48 Expert estimation of compatibility between modules (ASIT)

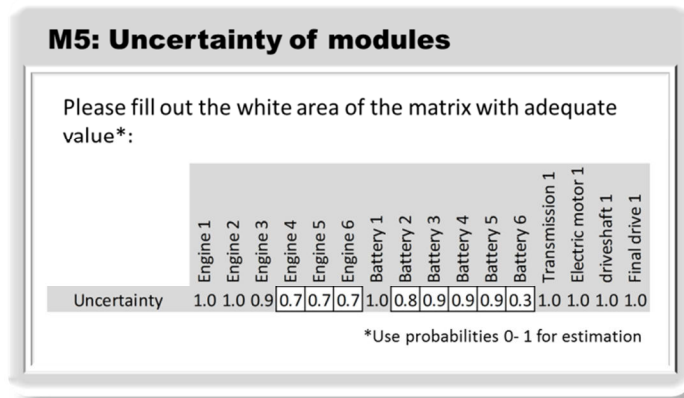


Figure 5-49 Expert estimation of module uncertainty (ASIT)

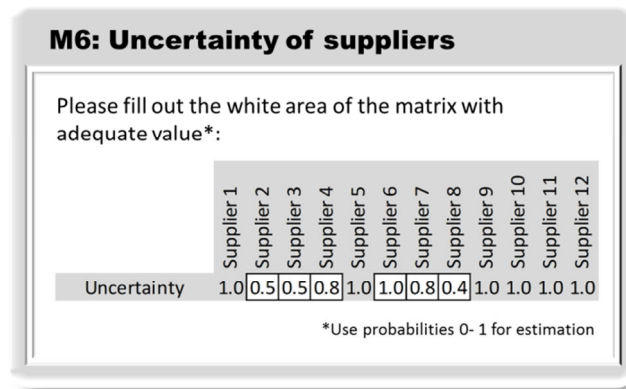


Figure 5-50 Expert estimation of supplier uncertainty (ASIT)

Similar to the results obtained using ASIT-E, shown in Fig.5-28, uncertainty and requirements satisfaction for possible architectures by using ASIT are shown in Fig. 5-51. Using the thresholds, 16 architectures out of 36 remain after filtering, as shown in Fig. 5-51.

Architecture	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Overall uncertainty	0.03	1.00	0.11	0.05	0.03	0.07	0.02	0.29	0.09	0.02	0.02	0.04	0.00	0.16	0.07	0.03	0.03	0.03
Requirement satisfaction	5.4	5.0	5.9	7.2	7.3	6.4	6.4	6.0	6.9	8.2	8.3	7.4	6.0	5.7	6.6	7.8	7.9	7.1
Architecture	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Overall uncertainty	0.01	0.34	0.08	0.03	0.03	0.04	0.02	0.30	0.05	0.02	0.02	0.03	0.01	0.02	0.01	0.00	0.00	0.01
Requirement satisfaction	6.2	5.8	6.8	8.0	8.1	7.3	5.5	5.2	6.1	7.3	7.4	6.6	7.0	6.7	7.6	8.8	8.9	8.1

Figure 5-51 Uncertainty and requirements satisfaction for possible architectures (ASIT)

In ASIT, only requirements satisfaction and uncertainty are considered, but not the environmental issues. Therefore, more concepts are identified using ASIT than using ASIT-E, as expected. The identified engine-battery combinations using ASIT-E and ASIT are shown in Fig. 5-52. The three concepts identified by ASIT-E are also identified by ASIT, which are represented by bold lines.

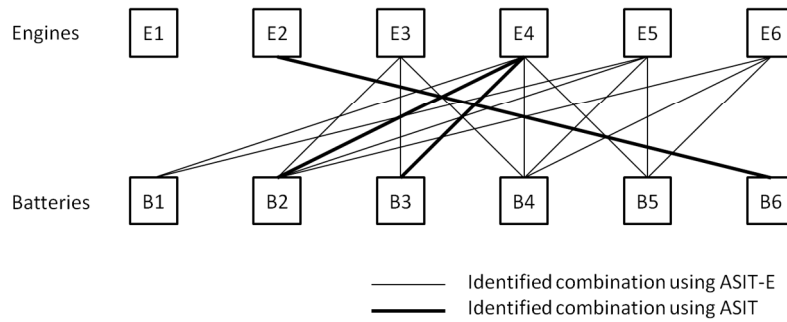


Figure 5-52 Result comparison of ASIT-E and ASIT

It can be seen from Fig. 5-52 that when environmental issues are not considered, engines 3, 5, 6, and batteries 1, 4, 5 are all among the identified concepts. However, according to RoHS, the material cadmium contained in battery 5 is among hazardous materials, and its utilization is restricted. Battery 1 (NiMH battery) uses approximately 4.5kg of rare earth metals, which is much higher than other batteries (which normally use around 1kg of rare earth). The battery 5 is eliminated because of the unsatisfactory condition of its supplier, who does not have ISO14001 certification, has low capability of using environmental friendly packaging, and at the same time out-dated public disclosure of environmental record. As for engines: engine 3 is filtered out by ASIT-E because of its high quantity of aluminium utilization, since aluminium is among the rare earth materials. Engine 6 is eliminated due to its supplier's incapability of using recycled materials, and the lack of public disclosure of environmental record. Finally, engine 6 is not among ASIT-E's final candidate list because of its unsatisfactory performance regarding CO₂ emission, water consumption and electricity consumption during its entire lifecycle.

5.6 Discussion

The comparison between ASIT-E and ASIT showed that the consideration of environmental issues can effectively weed out many options that have different types of environmental problems. By using ASIT-E, OEMs are able to have a general idea about all possible architecture options with regards to their environmental performances. Moreover, since ASIT-E is built upon ASIT, the architecture's requirements satisfaction capability and uncertainty are also estimated.

By integrating the environmental plug-in into ASIT, we also show the flexible structure ASIT affords to easily add plug-ins. One possible future work would be developing other plug-ins for ASIT to better manage cost, time-to-market, and other factors. The environmental plug-in itself is also very flexible. According to OEMs' different needs, the environmental indicators as well as lifecycle phases can also be customized.

However, there are several limitations of ASIT that should be acknowledged. Data collection at or access to data on potential suppliers is challenging. Although required for many countries, the public disclosure of environmental record of suppliers does not guarantee reliable information; however, more and more

suppliers have started to provide their eco-profile. In the near future, we believe that such disclosures will become code of practice for suppliers; until then, OEMs can also rely on expert estimation to get approximate environmental information.

Another limitation of this work is about methods for calculating the environmental indicators; different OEMs may have different interpretation of the same environmental indicator. Therefore, in this work, it is not practical to provide one indicator calculation method that can be used by all OEMs. Therefore, we focused on illustrating the overall structure of ASIT-E rather than proposing an indicator calculation method. However, we think that developing adequate methods for calculating environmental indicators is a very important issue, and should be investigated in the future.

5.7 Conclusion

This paper discusses the development rationale, and illustrates the utilization of a new early design support tool — ASIT-E, which aims at supporting OEMs in identifying environmental friendly concepts, and suppliers with better requirements satisfaction and lower uncertainty.

This tool is illustrated using the case of a plug-in hybrid vehicle powertrain design. Through comparison of ASIT-E results to those of a similar method that does not consider environmental issues, we see that ASIT-E affords weeding out of options that have environmental problems. The flexible structure of ASIT-E allows OEMs to customize it by defining their own environmental indicators, lifecycle phases, as well as methods for calculating different indicators.

Although most contemporary suppliers still do not fully share their eco-profiles, the introduction of environmental legislations and increasing demand of consumers should make data collection for ASIT-E easier in the future. The ASIT-E database also provides a list of necessary data for estimating environmental performance in early design.

5.8 Reference

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6

Conclusion and perspective

6.1 Conclusion

In this thesis, we proposed an Architecture & Supplier Identification Tool (ASIT) to support OEMs in modular complex systems design. The work is presented in three research articles.

In the first article (presented in Chapter 3), we proposed the core method of ASIT. ASIT is a customer requirements oriented method based on existing data and expert knowledge. ASIT is able to generate all possible architectures (considering new technologies and new suppliers), evaluate performance of architectures (including requirements satisfaction, and the overall uncertainty level regarding both architecture and its suppliers), and identify a limited number of architectures and suppliers that should be involved in the conceptual design phase with regard to the overall uncertainty of an architecture. The utilization of ASIT is illustrated using a powertrain design case study. It is difficult to find all data required by ASIT in OEMs' existing database. Therefore, we validated ASIT by comparing its result with other design support methods. Since there is currently no other decision support method for the Architecture & Supplier Identification phase, we compared ASIT with CSM, which is a well-known matrix-based approach for concept evaluation. One main difference between ASIT and CSM is that ASIT considers architectures and suppliers simultaneously while CSM considers only product concepts. Since ASIT is designed for the Architecture & Supplier Identification phase, where new technologies and new suppliers are integrated, another big difference between ASIT and CSM is that ASIT considers the overall uncertainty when evaluating architectures and suppliers, while CSM does not. The comparison of results showed that ASIT is able to identify architectures and suppliers with best customer requirements satisfaction while at the same time eliminating architectures and suppliers with high uncertainty level in order to manage the overall risk.

In ASIT, we considered three types of uncertainties when estimating the overall uncertainty: (1) uncertainty related to suppliers' capabilities to cooperate well with the OEM, (2) the probability that a module can be successfully developed, and (3) the compatibility between the modules. Since in the conceptual design phase information is extremely limited due to new technology and supplier integration,

performance evaluation mainly depends on expert estimation. Therefore, the expert estimation related uncertainty may also influence the estimation result thus change identified architectures and suppliers. In order to analyse the sensitivity of ASIT regarding expert estimation related uncertainty, in the second article (presented in Chapter 4), we compared candidates identified by ASIT with consideration of expert uncertainty and ASIT without considering expert uncertainty. The comparison showed that the expert uncertainty does not influence the identification result of ASIT, and that ASIT is robust.

In the third article (presented in Chapter 5), we developed an “environmental impact estimation” plug-in for ASIT in order to consider lifecycle environmental impact of architectures during performance estimation. By adding this plug-in into ASIT, we also demonstrated the possibility of considering other estimation factors in ASIT thus customize ASIT according to different needs of OEMs. A powertrain design case that is similar as was done in the first article is used to demonstrate utilization of the method.

6.2 Contribution

The most important contribution of this work is the proposition of a design decision support tool for the Architecture & Supplier Identification phase for modular design, which is the first candidate identification tool developed for this phase. System architectures and suppliers are considered simultaneously, using imprecise qualitative data due to the characteristic of this phase.

The proposed method (ASIT) is able to help OEMs to benefit from the flexibility of modular design by integrating new technologies and new suppliers at the architecture generation stage. Moreover, the requirements satisfaction, the overall uncertainty, as well as lifecycle environmental impact of architectures are considered in order to meet OEMs’ needs of controlling overall risk and environmental impact in early design stage.

According to different needs of OEMs, it is possible to add plug-ins into ASIT to estimate architectures and suppliers from different perspectives. The customization is shown in Paper#3, after adding an environmental impact control plug-in into ASIT.

This work also proposes a database structure for OEMs to store existing data and expert estimation more efficiently. Because of different situations that OEMs are currently in, data required by the database may not be available in all OEMs. The database structure proposed in this work also can serve as a directive to help OEMs to recognize the necessary types of data needed for exploring all possibilities and estimating overall architecture performance in the Architecture & Supplier Identification phase.

6.3 Limitations & Future Research Plans

Like all other estimation methods for early design, one of the major limitations of this work is the collection of data. Because of the integration of new technologies and new suppliers in the Architecture & Supplier Identification phase, the information of new options is extremely lacking. Therefore, although

ASIT strives to reduce the quantity of data required, OEMs still need to put in effort to build the database and greatly depend on expert estimation. For future works, improvements in reducing data required and in proposing better ways of data collection is necessary.

Regarding performance estimation of possible architectures and suppliers, this work considers three criteria: customer requirements satisfaction, overall development uncertainty, and product lifecycle environmental impact. Besides these three criteria, there are other factors that are good to consider in the Architecture & Supplier Identification phase, such as cost and lead-time. In existing methods, the estimation of these two factors usually requires massive quantitative data, thus unsuitable for the Architecture and Supplier Identification phase. In future works, adequate estimation methods of cost and lead-time, as well as other factors should be developed. Since ASIT is a framework that is easy to insert plug-ins. Authors can also develop performance estimation plug-ins of divers factors for ASIT, in order to get a more global estimation of architectures' performance.

In this thesis, the utilization of ASIT is illustrated by a powertrain design case. In future works, it will be interesting to test ASIT with more complex products and products in other industries. Because of different nature of products, it is possible that ASIT needs to be modified in other industries and for other products.

For more complex products, it will be interesting to use ASIT by different levels of decomposition. The number of modules that should be considered in each level of decomposition is limited by the fact that ASIT depends on expert estimation, thus has limited capacity for estimation. For example, when considering the design of an airplane, the airplane should firstly be decomposed into high level modules, then, each module can be decomposed again to lower levels. The ASIT can be used for each level of decomposition. However, the link within ASIT should be developed to be able to use estimation of lower levels directly in the estimation of higher levels. The ASIT can be used iteratively until the estimation of an entire product is done. Besides, the adequate number of modules to be considered during each decomposition should also be studied.

Personal Publications

Journal papers

- Yun YE, Marija JANCOVIC, Gül E. KREMER & Jean-Claude BOCQUET (2014). Managing Uncertainty in Potential Supplier Identification. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 28 (4).
- Yun YE, Marija JANCOVIC, Gül E. KREMER, Bernard YANNOU, Yann LEROY & Jean-Claude BOCQUET (2014). Integration of Environmental Impact Estimation in System Architecture & Supplier Identification. Submitted to *Research in Engineering Design*.
- Yun YE, Marija JANCOVIC & Gül E. KREMER (2014). Understanding the Impact of Subjective Uncertainty on Architecture Generation and Supplier Identification in Early Complex Systems Design. Submitted to *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems*.

Conference papers

- Yun YE, Marija JANCOVIC & Gül E. KREMER. Understanding the Impact of Expert Estimation Related Uncertainties on Architecture Generation and Supplier Identification. *IDETC 2014*, New York.
- Yun YE, Marija JANCOVIC & Jean-Claude BOCQUET. Main Factor Identification for Early Negotiation in Product Design. *ICED 2013*, Seoul.
- Yun YE, Marija JANCOVIC & Jean-Claude BOCQUET. Managing Semantic Consistency in Model-Based Systems Engineering Using a Matrix Structure. *IDETC 2012*, Chicago.

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Appendix

The proposed Architecture & Supplier Identification Tool (ASIT) is automated by a MatLab program. The main activities of ASIT are as shown in Figure 6-1.

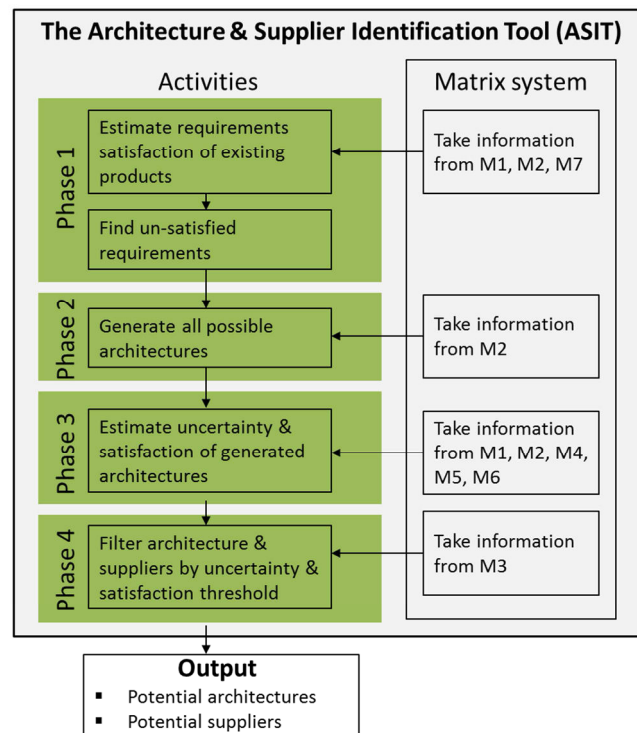


Figure 6-1 Main activities of ASIT

The main algorithm blocks are the followings:

1. Generate all possible architectures

```
function [Mapa] = all_possible_architectures (M2)

%GENERATE_ALL_POSSIBLE_ARCHITECTURES Generate all possible architectures
from combinations of components

% M2: module - function relations

% See also BLOCK_CYCLE
```

```

% Note: NO error (input, internal, etc.) handling

v_components = sum(M2, 2);

row_dimension = sum(v_components);

col_dimension = prod(v_components);

Mapa = zeros(row_dimension, col_dimension);

from_row = 1;

for component_idx=1:size(v_components,1)

cycle_length = prod(v_components(1:component_idx));
till_row = from_row+v_components(component_idx)-1;
block = block_cycle(v_components(component_idx), cycle_length);
Mapa(from_row:till_row, 1:end) = repmat(block, 1,
col_dimension/cycle_length);
    from_row = till_row + 1;

end

function [block] = block_cycle(number_of_components, cycle_length)

%BLOCK_CYCLE Generate all possible architectures from combinations of
components

% block = BLOCK_CYCLE(N, C) Builds a block (= matrix) based on number of
components N and cycle length C.

% Note that N must be whollydivisible by C; otherwise, an error is thrown.

% See also GENERATE_ALL_POSSIBLE_ARCHITECTURES

% Note: Hardly any error (input, internal, etc.) handling

if (mod(cycle_length, number_of_components) ~= 0)
error('Cycle length not divisble by # components.');
```

```

end

length_run_of_ones = cycle_length/number_of_components;
run_of_ones = ones(1, length_run_of_ones);

block = zeros(number_of_components, cycle_length);
block_row = zeros(1, cycle_length);
block_row(1:length_run_of_ones) = 1;

block(1,:) = block_row;
for idx = 2:number_of_components
block_row = circshift(block_row, [0 length_run_of_ones]);
block(idx,:) = block_row;
end

```

2. Estimate uncertainty & satisfaction of generated architectures

```
function [ Mca ] = uncertainty_of_architectures( Mapa, m4, m5,m36)

%UNCERTAINTY_OF_ARCHITECTURES calculates the overall uncertainty of each
architecture, considering module uncertainty, supplier uncertainty, and
compatibility

%Mapa: all possible architectures

%m4: compatibility

%m5: module uncertainty

%m36: supplier uncertainty - a combination of m3 and m6

Mca = zeros(1, size(Mapa,2));

%component number in architecture:
nb_component = size(find(Mapa(:,1)~=0),1);

%combination number of components in architecture:
ifnb_component~=0
nb_combination = nchoosek(nb_component,2)*2;
else
nb_combination=0;
end

for nb_col = 1:size(Mca,2)

%calculate maturity of module:
maturity_arch_vec_1 = zeros(nb_component,1);
maturity_arch_vec_2 = nonzeros(Mapa(:, nb_col).*m5);

for k1=1:size(maturity_arch_vec_2,1);
maturity_arch_vec_1(k1) = maturity_arch_vec_2(k1);
end

maturity_arch = prod (maturity_arch_vec_1,1);

%calculate uncertainty of suppliers:
maturity_sup_vec_1 = zeros(nb_component,1);
maturity_sup_vec_2 = nonzeros(Mapa(:, nb_col).*m36);

for k1=1:size(maturity_sup_vec_2,1);
maturity_sup_vec_1(k1) = maturity_sup_vec_2(k1);
end

maturity_sup = prod (maturity_sup_vec_1,1);

%calculte compatibility:
```

```

%1.generate a block for components of each architecture:
comp_block = repmat(Mapa(:,nb_col),1,size(Mapa,1));

%2.the compatibility matrix related to the architecture:
comp_matrix = comp_block.*m4.*(comp_block)';

%3.the product of compatibility:
[I,J] = find (comp_matrix);

V = zeros(nb_combination,1);

for k2 = 1:size(I,1)
V(k2) = m4(I(k2),J(k2));
end

comp_arch = sqrt(prod(V,1))

%certainty of architecture:
cert_arc = maturity_arch * comp_arch * maturity_sup;

Mca(1,nb_col) = cert_arc;
end

end

```