University of Twente

Faculty of Behavioural, Management and Social Science

Master Thesis

The Broken Mirror: not Merely Product Architecture Drives Firm Integration – also Knowledge does

Submitted by: Lena Alexandra Lauterbach (s1121413)

Contact Email: l.a.lauterbach@student.utwente.nl

1st Supervisor: Dr. ir. Erwin Hofman

2nd Supervisor: Dr. Matthias de Visser

Enschede, 22nd August 2016

Abstract

In the context of the discussion about the validity of the mirroring hypothesis (product architecture as a predictor of organisational design), this research mainly deals with the aspect of knowledge in terms of component and architectural knowledge as additional predictor of firm integration. The unique approach to apply the Design Structure Matrix on a complete product architecture is used as a tool to depict the component interdependencies of a tractor. Further, a large supplier survey provides extensive data of the variables knowledge in terms of component knowledge, and the variable buyer-supplier integration in terms of black- and grey-box development. The combined methods of qualitative and quantitative data show results that clearly reject the mirroring hypothesis as suggested by Sanchez and Mahoney. The original approach can be considered as too simplistic, since the relationship is contingent upon multiple factors of which supplier knowledge and buyer-supplier integration are significantly influencing aspects. More in depth and extensive research is required to capture the complexity of these relationships.

Keywords: Design Structure Matrix, product architecture, supplier component and architectural knowledge, buyer-supplier integration, grey- and black-box development

Table of Content

Index of Figures

Index of Tables

List of Abbreviations

A/C	Air Conditioning
AK	Architectural Knowledge
CK	Component Knowledge
DSM	Design Structure Matrix
EMEA	Europe, Middle East, Africa
GPE	Global Purchasing Excellence
KBV	Knowledge Based View
NPD	New Product Development
OEM	Original Equipment Manufacturer
RBV	Resource Based View
R&D	Research and Development
TCE	Transaction Cost Economics
VIF	Variance Inflation Factor

1. Introduction to the Research Paper

1.1. The Phenomenon of Product Modularity

The phenomenon of *modularity* in product and organisational design raised high attention among scholars (e.g. Fixson, 2007; Langlois, 2002; Sanchez & Mahoney, 1996; Ulrich, 1995) and among management practices (e.g. Brusoni & Prencipe, 2006; Hsuan, 1999) particularly in the late 1990s and early 2000s. The concept of modularity gained popularity as this enables an organisation to make use of modularity as strategy to offer product flexibility in regard to extended product variety (Patel & Jayaram, 2014; Salvador, Forza, & Rungtusanatham, 2002), hence an important source of strategic flexibility (Sanchez, 1995). The ability to offer extended product variety based on product modularity allowed organisations to make use of the benefits of mass customisation; for instance, one-to-one mapping of modular products enables independent design, development and production of components. This is based on the idea that product architecture corresponds to organisational architecture, according to the well-known mirroring hypothesis by Sanchez and Mahoney, implying independent design and production of modular components. However, extensive and industry-wide outsourcing had, among others, the consequences of high dependency on supplier, component and architectural knowledge decay and decreased product performance (e.g. Becker & Zirpoli, 2011; Hsuan, 1999; Ro, Liker, & Fixson, 2007).

Numerous cases and studies reveal that the mirroring hypothesis as proposed by Sanchez and Mahoney is not as simplistic as assumed, rather it is contingent in nature (e.g. Furlan, Cabigiosu & Camuffo, 2014). Researchers have widely discussed what factors additionally impact the relationship between product architecture and firm integration. The numerous factors such as pace of technology (e.g. Becker & Zirpoli, 2011; Takeishi, 2002), regular project versus new product development (NPD) (Becker & Zirpoli, 2011; Takeishi, 2002), degree of strategic importance of components (Hsuan, 1999), underline the complexity of the relationship between product architecture in regard to the strength of component coupling, and the disagreement among scientific researchers. Knowledge in general, and especially component and architectural knowledge, plays a major role in literature that is above all in connection with the mentioned factors. Many scientific authors underline the importance of knowledge, such as:

- Keeping certain degrees of component and architectural knowledge in-house to avoid knowledge erosion and to maintain (specialised) competences and skills (Araujo, Dubois, & Gadde, 2003; Furlan, Cabigiosu & Camuffo, 2014)
- Architectural and component knowledge ensure successful system integration for enhanced product performance (Cabigiosu, Zirpoli, & Camuffo, 2013; Takeishi, 2002)
- Close ties to suppliers for the means of knowledge acquisition and access to innovation, are especially important for (modular) NPD (e.g. Becker & Zirpoli, 2011; Cabigiosu et al., 2013; Furlan et al., 2014)
- Firm boundaries dependent on task and knowledge partitioning (Araujo et al., 2003; Becker & Zirpoli, 2011; Hoetker, 2006)

These findings unambiguously show the critical impact particularly on firm integration. It is suggested by Brusoni and Prencipe (2001) that *firms know more than they do*, which is an indication that despite black-box development, firms retain and develop knowledge for instance through constant information exchange and close buyer-supplier relationships – as opposed to loosely coupled relationships, and design and production independence.

To date, researchers clearly have questioned the original mirroring hypothesis in such a way that is regarded as insufficient due to the complexity that is in association with products and organisational decisions, boundaries, and internal and external factors. Furthermore, architectural and component knowledge are considered as highly critical factors that are in connection with further aspects impacting the relationship. Nevertheless, disagreement is present on how and in which way component and architectural knowledge additionally affect the original mirroring hypothesis. Especially lacking is research concerning a complex product system, as mostly single modular systems are subjects to research, such as the air conditioning system (Cabigiosu et al., 2013; Pimmler & Eppinger, 1994; Zirpoli & Camuffo, 2009), aircraft engines (Sosa, Eppinger, & Rowles, 2003), and aircraft engine control systems (Stefano Brusoni, Prencipe, & Pavitt, 2001).

Within the context of master thesis project, this research is conducted under supervision of Dr. ir. Erwin Hofman and in collaboration with Justus E. Eggers, writing his PhD dissertation about module development in relation to buyer-supplier integration (supervised by Dr. ir. Erwin Hofman).

The research aims to shed light on the additional impact component and architectural knowledge have on the relationship between product architecture and firm integration, as assumed by the mirroring hypothesis. The product architecture in terms of component coupling and the supplier's level of component and architectural knowledge will be related to the level of buyer-supplier integration in terms of black- and grey-box development in order to identify in which way product architecture, knowledge and buyer-supplier integration are related to each other.

The research method is a combined approach of qualitative and quantitative research. This approach underlies an explorative nature as data is collected through interviews to create a product architecture matrix on the one hand and surveys distributed to suppliers on the other hand. The interviews represent the qualitative part in this research, in which engineers were asked to fill out the Design Structure Matrix (DSM) in order to depict the component interdependencies of the product architecture by the example of a tractor. The DSM is used as a tool to show component and system interdependencies, indicating modular and integral component systems. The survey data will be statistically analysed (regression analysis) under the aspects of what degree and type of knowledge the supplier owns, the degree of buyer-supplier integration. These outcomes are linked to the outcomes of the DSM with the focus on a) type of component development approach in relation to the respective component coupling, b) supplier knowledge (component and architectural) in relation to component coupling and c) level supplier component and architectural knowledge in relation to the degree of buyer-supplier integration. Collected interviews and survey data are based on a multinational organisation and its suppliers. This organisation, a large and worldwide acting manufacturer of agricultural machinery is an ideal example from real life, because the results can be considered as more generalizable due to its organisational size enabling larger scopes and scales. Further, the example of a tractor is transferable to other vehicles, such as automobiles due to their construction similarities.

From the suppliers' perspective, the final results suggest a clear dominance of grey-box development over black-box development. Level of knowledge is generally high, whereas component knowledge is stronger in comparison to architectural knowledge. There is a significant relationship recognisable between component coupling and component knowledge with grey-box development. In turn, component coupling is not related to black-box development, which however is predicted by architectural knowledge and combined architectural and component knowledge.

The research paper is structured into four core parts: chapter one to three reflect an introduction of the topic and the company, the underlying theories related to the research issue and the research concept including the research model, questions and hypotheses. Chapter four to seven include intensive literature reviews that emphasise the most important findings about product architecture, component and architectural knowledge, and buyer-supplier integration. In the following (chapter eight and nine) the research methodology will be outlined, and the data collection measurement approach explained. The final part includes the qualitative and quantitative analyses of the results of the DSM matrix and surveys (chapter ten, eleven and twelve). In the following, these will be linked to the literature review findings, and finally discussed and summarised as the last step (chapter twelve).

1.2. Introduction of the Organisation: a Worldwide Group Specialised in Manufacturing Agricultural Equipment

For means of anonymity and data confidentiality the organisation is renamed. Information about this organisation are based on the company website and the annual reports of 2015 and 2014. Established from a buy-out in 1990, the agricultural corporation ABC is a multi-national organisation today, which specialises in designing, manufacturing and distributing agricultural equipment. Various core brands belong to the company ABC, whose distinctive brand names remain. In addition to the core brands, ABC incorporates 3000 dealers located in over 140 countries worldwide.

Agricultural equipment includes tractors, combines, hay tools, sprayers, planters, forage, equipment, gain storage and protein solutions, seeding and tilling implements, and replacement parts. Among the range of products, tractors represent the largest portion of sales worldwide (57%), followed by replacement parts (16%), and gain storage and protein production equipment (both 10%). The largest market represents EMEA (Europe, Middle East, and Africa) with a net sale of 56 per cent, followed by North America (26%) and South America (13%). The numbers refer to the numbers provided by the annual report of 2015.

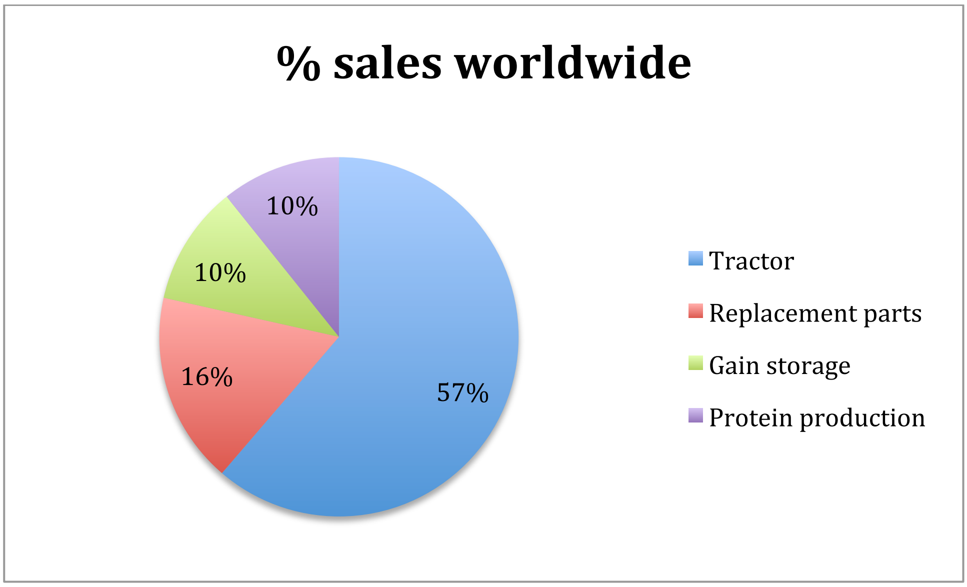

Figure 1 (own image): Percentage sales of products

ABC has a focus on offering enhanced, efficient and innovative products to its customers, aiming at supporting farmers' efficiency and productivity. Therefore, innovative products and the development of improved leading-edge technologies are key to ABC's business supported by high investments in R&D, engineering and the improvement of operational processes; production and delivery in particular. The introduction of a new product family of mid-sized tractors occurred in 2014, which are based on a modular design in order to offer higher product and manufacturing flexibility. Modular platforms include engines, transmissions, rear axles, cabs and operator stations. Furthermore, the Global Purchasing Excellence (GPE) has been introduced, a worldwide program that changed the previous factory-based purchasing function into new global commodity-based purchasing teams. Global commodity-based teams are suggested to have better market and product knowledge, in combination with global sourcing expertise to improve purchasing decisions and cost saving.

2. Explaining the Relationship between Product Modularity and Firm Boundaries by Transaction Cost Economics and Knowledge Based View

2.1. Modularity as Means to Lower Transaction Costs due to Organisational Design Interdependencies

The review of numerous academic articles regarding component, architectural knowledge, organisational integration and product modularity are largely embedded by Transaction

Cost Economics (TCE) according to Williamson, (e.g. 1979) and Knowledge Based View (KBV) according to Grant (1996). Besides TCE and KBV, the Social Network Theory (Gokpinar, Hopp, & Iravani, 2010; Sosa, Eppinger, & Rowles, 2007; Sosa, Gargiulo, & Rowles, 2007) and Contingency Theory, more precisely Task Contingency Theory (Colfer & Baldwin, 2010; Furlan, Cabigiosu, & Camuffo, 2014; Kalaignanam, Kushwaha, & Nair, 2015), are applied as underlying theories to explain the relationships. Furthermore, Resource Based View (RBV) (Becker & Zirpoli, 2011; Ron Sanchez, 1995) and Capabilities View of a Firm (Araujo et al., 2003; Zirpoli & Camuffo, 2009) are applied, but those theories play a minor role in academic literature.

Given their dominance the focus of the review is on TCE and KBV. Both theories are often combined and serve research to provide theoretical explanation about firm boundaries in association with product modularity (Baldwin, 2008; Becker & Zirpoli, 2011; Colfer & Baldwin; 2010; Hoetker, 2006).

Transaction Cost Theory is originally developed by Coase, 1937 and gained popularity through Williamson's elaborations, for instance by his article "Transaction-Cost Economics: The Governance of Contractual Relations" (1979) and his book "The Economic Institutions of Capitalism" (1985). *Transactions* itself are defined as "mutually agreed transfers with compensation and are located within the task network" (Baldwin, 2008), or as "reciprocal exchange based on some degree of mutual understanding" (Baldwin, 2008). Therefore, a prerequisite for a transaction to take place is that both parties perceive the specifications as beneficial and advantageous to such an extent that those outweigh the trading costs (Jacobides et al., 2011). TCE suggests that through transactions firms aim at profit maximisation and risk minimisation (Hoetker, 2006; Williamson, 1985). According to Teece (1977), transaction costs are associated with cost incurred by (1) cost of pre-engineering technological exchanges, (2) engineering cost (product design and product engineering), (3) R&D (research and development) personnel (salaries and expenses, costs for product technology modification and adaption), (4) pre-start-up training cost and the excess manufacturing costs.

Williamson identifies three attributes of contracting processes, namely *bounded rationality*, *opportunism* (both comprised by behavioural assumptions) and *asset specificity* (Williamson, 1985). *Bounded rationality* represents the cognitive assumption, which suggests that transactions are accompanied with bounded rationality of the actors due to limited competences (Williamson, 1985). *Opportunism* involves the self-interest of each party: ”incomplete or distorted disclosure of information, especially to calculated efforts to mislead, distort, disguise, obfuscate or otherwise confuse” (Williamson, 1985), which causes information asymmetry (p. 46). As opportunism is initiated by behavioural uncertainty, it is suggested that governmental structures act as bounding rules for acting parties to support building trust, a further aspect that lowers the risk of opportunism (Williamson, 1985). *Asset specificity* refers to the uniqueness of assets, physical and non-physical assets such as human resources, which are claimed to be the firm’s raison d’être. Acquisition of assets implies learning as it involves undisclosed procedures requiring managerial and technical skills and know-how (Williamson, 1985).

Important concepts of TCE that underlie bounded rationality, asset specificity and opportunism are *uncertainty* and *transaction frequency.* Uncertainty is triggered by the lack of trustworthiness due to ignorance of relevant information (Williamson, 1998), which in turn is increased by the presence of asset specificity and on the contrary, reduced through repeated transactions (transaction frequency) (Williamson, 1985). In order to reduce the risks related to transactions, it is proposed that firms organise their operations and productions around long-term internal and external suppliers to facilitate eased communication and trust building. Hence, TCE proposes that firms are tightly coupled and rarely reconfigure their supply chain (Hoetker, 2006). Consequently, scholars suggest that modularity creates new buyer-supplier boundaries including low transaction costs as thick relational ties become obsolete (Baldwin, 2008; Hoetker, 2006). This assumption, and therefore TCE, but also KBV are consistent with the mirroring hypothesis by Sanchez and Mahoney (Brusoni et al., 2001; Colfer & Baldwin, 2010; Furlan et al., 2014). Under the assumption of mainly TCE and to a lower extent KBV, Baldwin (2008,) investigates the relationship of firm boundaries and product modularity. The main findings reveal that modularisation establishes new firm boundaries with relatively low transaction costs (Baldwin, 2008). This is reasoned by so-called thin crossing points, in which labour is divided between two parties / domains and most information is hidden that requires only few transfers of energy, material and information. In respect to the Knowledge Based View, knowledge and tasks can be divided by two firms and facilitate organisational independency. The crossing points are thinner across modules than within modules (Baldwin, 2008). In contrast, thick crossing points involve frequent complex, uncertain and iterative transfers, which require formal contracts and repeated buyer-supplier interaction (Baldwin, 2008).

In line with the design theory that assumes “if two designs are interdependent, each is specific to each other” (Baldwin, 2008, p. 170), design interdependence is in association with increased asset specificity involving uncertainty, complexity and frequent interaction that are revealed by thick crossing points (indication integrated design) (Baldwin, 2008; Brusoni et al., 2001). This is also supported by Mikkola (2003), who argues that the degree of buyer-supplier interdependence can be recognized in terms of asset specificity vis-à-vis the assumptions of TCE. Furthermore, asset specificity raises opportunistic behaviour, due to the impossibility to measure and value each transaction and the therewith-involved incompleteness of contracts (Baldwin, 2008).

Modularisation is therefore considered as a means to make thick crossing points thinner, as asset specificity and uncertainty of the transaction causing opportunistic behaviour are reduced (Baldwin, 2008). However, Furlan et al. (2014) underline that under the presence of a highly dynamic technological environment, modularity is not a factor lowering transaction costs.

2.2. Knowledge Based View as Theory Explaining Firm Boundaries in Regard to Knowledge and Task Partitioning

KBV can be regarded as an extension of TCE (Hoetker, 2006) that is primarily used to explain firm boundary decisions based on task and knowledge partitioning (Baldwin, 2008; Becker & Zirpoli, 2011; Jacobides & Winter, 2005; Takeishi, 2002; Zirpoli & Camuffo, 2009).

Based on Grant (1996), KBV implies that firms aim at maximisation through eased communication between the involved units in a product design process, facilitated by knowledge transfer (Hoetker, 2006). Grant (1996) claims that knowledge is resided in individuals and firms are required to integrate the individuals’ knowledge into services and goods. Knowledge integration involves the establishment of coordination mechanisms on the one hand and inter-firm co-operation for the means of knowledge transfer, access and exchange on the other hand. The latter aspect is in regard to decisions about, and the impact on firm boundaries. Grant suggests that the boundaries of a firm (vertical and horizontal) are dependent on how efficiently a firm utilises knowledge. Efficient knowledge utilisation is defined as congruence between the knowledge domain of a firm and product domain. Perfect congruence between knowledge and product does not exist. Moreover, the imperfect congruence creates horizontal gaps between firms and in turn, facilitates opportunities and advantages for a firm to make better use of knowledge, for instance through strategic alliances (Grant, 1996).

Baldwin (2008) adds that knowledge-based theories of the firms have different theoretical approaches, whereas the theories agree to following points: (1) focus on what is happening inside a firm or organisation, (2) firm value derives from a firm's abilities in terms of routines, capabilities and competencies, that are difficult to imitate, (3) recognition that capabilities, routines and competences are knowledge-based, resided in individuals that must be assembled and reconfigured.

Firms build capabilities around internal and external knowledge in order to economise the production and the exchange of knowledge. In this way boundaries are shifted according to the changed routines, capabilities and competences, which also refer to the span and scope of knowledge of a firm. Through shifting boundaries, the aim is to minimise knowledge overlaps between firms, leading to task independence and information hiding in respect to TCE, indicating modularity in product design according to the understanding of KBV (Baldwin, 2008). A similar conclusion is provided by Zirpoli and Camuffo (2009), who assume that the interdependencies between product architecture, firm boundaries and knowledge (industry knowledge, types and scope of knowledge) a firm has to deal with, are largely influenced by task and knowledge partitioning decisions by the firm, thus an theoretical explanation is embedded in KBV. Again, the idea of knowledge and task partitioning and coordination of a firm in order to achieve interdependence and to avoid knowledge overlap, corresponds to the idea of the mirroring hypothesis (Colfer & Baldwin, 2010).

Concluding it can be stated that both theories, TCE and KBV provide explanation of firm boundaries by (1) product and organisational independence (modularity) lower transaction costs due to reduced asset specificity and uncertainty, and (2) knowledge and task partitioning aiming at avoiding knowledge overlap by means of independence and modular products. Both approaches, also often in combination, enable the shifting of firm boundaries to benefit from modularisation.

3. Research Goal and Research Model Aim at Investigating the Relationship between Product Architecture and Buyer-Supplier Integration Including Additional Influence of Supplier Knowledge

3.1. Product Architecture and Supplier Knowledge as Predictor of Buyer-Supplier Integration

It is suggested by numerous scientific articles that not merely product architecture is a driver of inter-firm coordination but also knowledge in terms of component and architecture knowledge. While the relationship between product architecture and buyer-supplier interaction still remains, knowledge can be regarded as additional influencing variable whose impact is shown in several cases. However, a sound explanation concerning how these variables are related to each other has not been developed yet. To date, it can be stated that the original mirroring hypothesis is not rejected per se. Moreover, emphasis has been laid on intrinsic aspects such as relational and knowledge related, and behavioural aspects, which have been taken into consideration when attempting to find a more complete and integrative explanation for the mirroring hypothesis. Based on recent literature findings, the following research model is developed (figure 2). In this model, supplier component and architectural knowledge act as additional independent variable that changes the original relationship, namely product architecture (independent variable) as influencer of buyer supplier integration (dependent variable) in terms of black- or grey-box development. The main reason for choosing (supplier) knowledge (component and architectural) is based on the dominating view of the recent literature. Other variables are also identified that particularly refer to a firm's sourcing approach, such as component's or product's pace of technology, degree of strategic importance for the firm and the supplier's perception of the customer status. With this in mind, the dominance of knowledge is given by various argumentations referring to maintaining a certain level of knowledge associated with keeping control over processes, supplier knowledge and information sharing and therewith-involved mutual involvement in the respective product development steps (see literature review).

In order to analyse this relationship as depicted in the research model, the product architecture including its component interactions of a tractor serves as main research objective. By analysing the interaction and interrelations of the tractor components the research aim is to investigate the impact (supplier) component and architectural knowledge have on the relationship between product architecture and buyer-supplier interaction (mirroring hypothesis). This will be conducted through a supplier perspective in order to identify contingencies related to product architecture as well as evaluating different levels of innovativeness – both are likely to be affected by the level of knowledge.

Based on the research goal, the research question is as follows: *In which way do component and architectural knowledge, and product architecture influence the degree of buyer-supplier integration?*

As a final note, it can be stated that agricultural machines as produced and developed by ABC belong to the agricultural equipment industry. However, since the focus lies on the component analysis of a tractor, it is therefore related to the product family of vehicles. Due to this, the architectural structure of a tractor has similarities with the architectural structure of an automobile; hence, scientific findings particularly from researches within the automotive industry are used to develop the research question, sub-question and the research model and hypotheses.

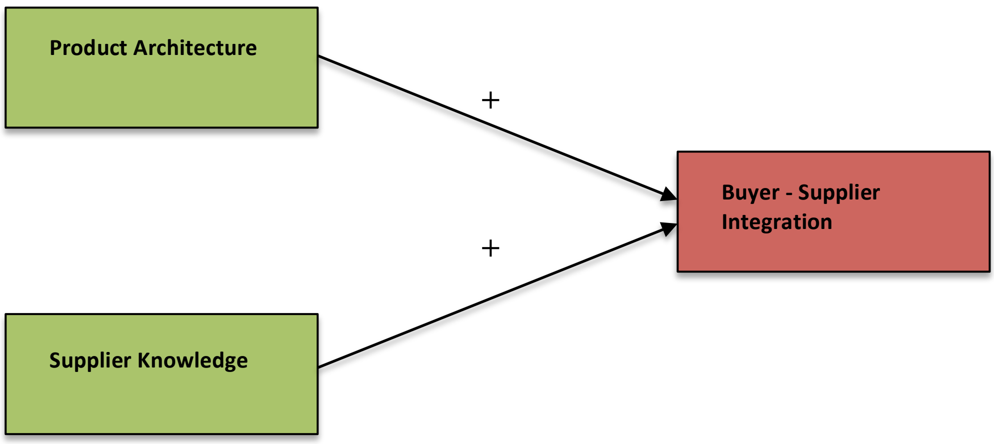

Figure 2 (own image): Research model

3.2. Research Questions and Sub-Research Questions

As mentioned above, this research aims at investigating the additional impact knowledge has on the relationship between degree of product architecture (modular to integral) and the level of buyer-supplier integration, in regard to black-box or grey-box sourcing. Therefore, the main research question is:

In which way do component and architectural knowledge, and product architecture influence the degree of buyer-supplier integration?

In order to fully answer the main research question, the following sub-research questions are developed:

1. How can the product architecture of the tractor be characterised in terms of component interactions and component coupling?
2. What are the suppliers' levels of component and architectural knowledge?
3. How does the product architecture in terms of component coupling effect the level of buyer-supplier integration?
4. How is the degree of buyer-supplier integration related to the suppliers' level of component and architectural knowledge?

3.3. Definition of Main Terms

Prior to reviewing the literature on product architecture, component and architectural knowledge and firm integration, the most relevant terms are provided with respective definition, to ensure a common understanding:

Component: "[…] separable physical part or subassembly (Ulrich, 1995, p. 421).

Product architecture: defined by interface strength, "[…] (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components" (Ulrich, 1995, p. 420).

Modular Architecture: (1) "[…] one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components" (Ulrich, 1995, p. 422); (2) "A special form of product design that uses standardized interfaces between components to create a flexible product architecture" (Sanchez & Mahoney, 1996, p. 66).

Integral Architecture: "[…] complex (non one-to-one) mapping from functional elements to physical components and/or coupled interfaces between components" (Ulrich, 1995, p. 422).

Modularity: "[…] special form of design which intentionally creates a high degree of independence or 'loose coupling' between component designs by standardising component interface specifications" (Sanchez & Mahoney, 1996, p. 65).

Buyer-supplier integration (interaction): is defined as the degree of information sharing between buyer and supplier (Cabigiosu & Camuffo, 2012)

Component knowledge: "[…] knowledge about each of the core design concepts and the way in which they are implemented in a particular component" (Henderson & Clark, 1990, p. 11).

Architectural knowledge: "[…] knowledge about the ways in which the components are integrated and linked together into a coherent whole" (Henderson & Clark, 1990, p. 11).

Black-box design: "In a black-box design environment, suppliers carry out product engineering activities on behalf of their customers and even develop components or entire subassemblies" (Koufteros, Vonderembse, & Jayaram, 2005, p. 102).

Grey-box design: "In a grey-box environment, the supplier's engineers work alongside the customer's engineers to jointly design the product so the supplier's process can be effectively integrated with the design" (Koufteros et al., 2005, p. 102).

4. Mirroring Hypothesis: Product Architecture "Mirrors" Organisational Design

4.1. Mirroring Hypothesis as Universal Theory Explaining the Relationship Between Product Architecture and Firm Integration

The independent design, development and production of a modular component is in relation to the mirroring hypothesis given its main idea that the architecture of a product is mirrored in the organisational design (Sanchez & Mahoney, 1996, p. 64): "[…] the creation of modular product architectures not only creates flexible product designs, but also enables the design of loosely coupled, flexible 'modular' organization structures" (Sanchez & Mahoney, 1996, p. 73). According to Sanchez and Mahoney (1996), a modular organisational design can be facilitated due to specification of required outputs that allow task partitioning, which can be performed autonomously and concurrently by a loosely coupled organisation. It is based on the idea that it is easier to deal with a complex product when this is decomposed into sub-assemblies in order to partition and divide the related tasks, such as design and production (Colfer & Baldwin, 2010). As Colfer and

Baldwin describe: "[…] the design of a complex product system, the technical architecture division of labour and division of knowledge will mirror one another in the sense that the network structure of one corresponds to the structure of the others." (Colfer & Baldwin, 2010, p. 4). The principles of the mirroring hypothesis are *information hiding*, *division of labour*, and *division of knowledge. Information hiding* reveals that information is hidden within a module, which implies that teams/firms/individuals (under modularity) can work independently without information exchange that results in a one-to-one mapping of the product architecture. *Division of labour* refers to allocation of design tasks among individuals/firms/teams along organisational ties that include communication, collocation, and co-membership. *Division of knowledge* refers to the way design tasks and the relevant information are distributed among involved teams/people (Colfer & Baldwin, 2010).

By reviewing 102 studies, within firms, across firms and open collaborative firms (p. 11), Colfer and Baldwin (2010) largely found support for the mirroring hypothesis (69%), while findings reveal that the support was strongest in within-firm samples, less strong in across-firm samples and weakest in open community-based samples. The within-firm samples mainly deal with maintaining and achieving congruence between organisation and product, whereas the exact of product and organisation is a desirable state and difficult to achieve and especially to maintain (Colfer & Baldwin, 2010). The research by Amrit and van Hillegersberg (2008) serves as an example article, concluding that the collaboration between developers, designers and testers should be in relation and in accordance to the structure of the technology in question. Additionally, Puranam, Singh, and Chaudhuri (2009) state that it is the common ground and knowledge that reduces the need for formal coordination ties and mechanisms. Noteworthy, the redesign and introduction of modular products involve high levels of coordination and close collaboration of teams (Colfer & Baldwin, 2010).

4.2. Support of Mirroring Hypothesis Indicated by Dominant Design on Industry Level and Product Stability on Firm Level

While within-firm samples show 74 per cent support for the mirroring hypothesis, across-firm samples indicate a support of 47 per cent (23% partial and 5% mixed support). The across-firm group has the largest number of samples (62) (22 within-firm samples, 7 open collaborative firm samples) (Colfer & Baldwin, 2010). Support for the mirroring hypothesis is primarily emphasized by the concept of *dominant design* on the industry level: a new technology becomes an industry wide standard, while the industry structure adapts to the product design (Colfer & Baldwin, 2010).

With focus on across-firm samples, the mirroring hypothesis is consistent with the approaches of transaction cost theory and knowledge-based view, as main underlying theories. On the firm (micro) level studies deal with organisational issues such as sourcing decisions, supplier-alliance decisions, outsourcing, and product innovation. These samples underline that integral product architecture is in correlation with 'insourcing', leading to enhanced product performance, while a modular product architecture is in association with outsourcing (Colfer & Baldwin, 2010).

Especially across-firm results are important to this study, as these investigate buyer-supplier integration under product modularity as one key variable of the research. In regard to across-firm relationships, the mirroring hypothesis implies that component design, development and production, can be fully outsourced to suppliers, which is in line with the idea of black-box development. A modular project works well if they are defined ex ante and the components remain stable throughout the product and project life and if the components can be coupled and de-coupled independently (Cabigiosu, Zirpoli, & Camuffo, 2013).

The importance of product architecture stability of modular products can be considered as a critical aspect influencing the relationship between the product and buyer-supplier integration, as indicated by several studies (Brusoni et al., 2001; Cabigiosu & Camuffo, 2012). Cabigiosu and Camuffo (2012) find support for the mirroring hypothesis (H1) at component level and under the condition of product architecture stability. H1 states: "When a buyer designs more modular components (ex ante), there is less information sharing between the buyer and component suppliers (ex post)" (Cabigiosu & Camuffo, 2012, p. 688). Similar findings were made by Fixson, who stresses that the mirroring of the product structure in these domains/product development processes is more likely in stable industries that additionally enable incremental learning and product development (Sanchez & Mahoney, 1996). Fixson (2005) indicates that the product architecture in terms of its level of complexity and its characteristics impacts managerial and organisational decisions regarding design, operation and numerous domains of product, process and supply chain.

An additional confirmation for the mirroring hypothesis stating that high levels of component modularity negatively moderate the direct relationship between buyer-supplier information-sharing and the performance of supply relationships (H2B), is consistent with the main idea of mirroring hypothesis according to Sanchez and Mahoney: "[…] standardized component interfaces in a modular product architecture provide a form of (ex ante) embedded coordination that greatly reduces the need for overt exercise of managerial authority to achieve coordination of development processes, thereby making possible the concurrent and autonomous development of components by loosely coupled organization structures" (Sanchez & Mahoney, 1996, p. 64). Cabigiosu and Camuffo (2012) propose that a high degree of product modularity is associated with either high levels of information sharing (complementary hypothesis) or low levels of information sharing (trade-off hypothesis). High and low levels of information sharing could be either driven by ex post or ex ante specification and definition respectively; both are not mutually exclusive.

Furthermore, it s argued that modularity in product and organisational design enables eased switching of suppliers, which implies that arm's length relationships are more suitable to close supplier relationships on the one hand (Hoetker, 2006), and the independent operation of buyer and supplier involving reduced coordination effort on the other hand (Sosa, Eppinger, & Rowles, 2004).

4.3. Mirroring Hypothesis Provides Insufficient Explanation Due to Contingent Nature of the Relationship

As mentioned, 23 per cent of the across-firm studies show partial support and five per cent mixed support that largely complies with the own literature findings. Interestingly, findings according to Colfer and Baldwin (2010) reveal that firms outsource modular products in terms of task partitioning, but oppose the principle of information hiding. Firms share information frequently in order to coordinate their joint work – according to "firms know more, than they do" (Brusoni & Prencipe, 2001, p. 202). This supports the assumption that the mirroring hypothesis (at least at across-firm level) is not as simplistic as suggested by Sanchez and Mahoney, but rather "contingent in nature" (Furlan et al., 2014, p. 801). Furthermore, the study by Colfer and Baldwin supports the importance of knowledge as a critical factor influencing the mirroring hypothesis, emphasising the insufficiency of the original mirroring hypothesis.

In a research paper by Zirpoli and Camuffo (2009) it is investigated to which extent product architecture is the main driver of an inter-firm coordination and decision-making. Findings reveal, it is not the product architecture per se, which is a main driver of inter-firm coordination and design tasks. It is implied that additional drivers need to be taken into account in a co-development project:

- Knowledge-sharing and involvement in component design (vertical integration)
- Equifinality: "[…] diverse task partitioning and inter-firm coordination led to equivalent outcomes" (Zirpoli & Camuffo, 2009, p. 259)
- Consistent original equipment manufacturer (OEM) (and supplier) behaviour as prerequisite for a successful modular new product development (NPD)

The main findings of the research paper imply that product architecture is not observed as a main driver of a buyer-supplier relationship, and the existence of intense information sharing and two-way learning characterise the buyer-supplier relationship (Zirpoli & Camuffo, 2009).

A case study by Brusoni and Prencipe (2006) involving a radical change within a tire manufacturing organisation depicts the evolvement and establishment from old to new design rules. By introducing a Modular Integrated Robotised System (MIRS) the company enables production flexibility, small batch production of differentiated tires and fulfilment of specific engineering requirements. Hereby, a trend towards an increased need for flexibility, automation and customised products is followed. Changes occur within knowledge, technology, production processes, organisational domains and the product. As robotised production techniques require integrated versus specialised and articulated versus tacit knowledge processes, the development and adoption of new design rules were necessary. Findings suggest that the adoption of modular design principles for tires and plant did not lead to a modular organisation – as the mirroring hypothesis assumes – but more importantly: a modularisation of the production processes and plant involve a de-modularisation and integration at the organisational level. Therefore: "It is not the products that design organizations. Knowledge does." (Brusoni & Prencipe, 2006, p. 186).

Similar findings to Brusoni and Prencipe (2006), and Zirpoli and Camuffo (2009) were emphasised in a case study by Cabigiosu et al. (2013). By providing two examples of an automotive air conditioning (A/C) producer, which develops and produces A/C systems for two different car manufacturers, Cabigiosu et al., (2013) are able to analyse two different approaches:

(1) Project ALPHA:

- High component specific knowledge and ex ante definition of A/C specification

- Stable and detailed interfaces
- Not a black-box sourcing (high level of ex ante interface standardisation) due to frequent and intrusive involvement of ALPHA
- Higher control of technical interdependence

(2) Project BETA:

- Lower level of component specific knowledge with higher reliance on supplier's competence to modify and adjust AC system architecture
- Fluid and changing interfaces
- OEMs lack of component specific knowledge compensated with intense mutual adjustment, information sharing and structured inter-organisational procedures

Main findings suggest that standardised and stable interfaces do not necessarily lead to black-box development, as can be seen in project ALPHA. This is contrary to the dominating assumption in academics, such as earlier findings by Zirpoli and Camuffo (2009). The authors describe a black-box outsourced component as possessing a "stable architecture and mature technological content, with a clear cut of tasks and knowledge partitioning between OEM and supplier" (Zirpoli & Camuffo, 2009, p. 253). Further, in a black-box new product development (NPD), the component interface is defined and specified (ex ante) by the OEM, who, in this case, has high component and architectural knowledge.

4.4. Importance of Firm Integration and Knowledge to Ensure Product Performance Independently of Product Architecture

These articles show that the original mirroring hypothesis is rather insufficient as additional drivers explaining modularity in product design and organisational design need to be taken into account equally. Primarily component and architectural knowledge owned by the supplier and buyer respectively are regarded as critical and important drivers. A further aspect that contradicts the mirroring hypothesis is the intensive buyer-supplier relationship and coordination, which is required throughout all project stages independently from the degree of modularity, to ensure product performance and overall quality (Kalaignanam, Kushwaha, and Nair, 2015).

In addition to the discussion concerning the mirroring hypothesis, a research paper by Zirpoli and Becker (2011) points out the limitations of outsourcing modular systems by the example of another automotive manufacturer. Findings indicate the significance to possess architectural and component knowledge and competences to such an extent that the OEM is able to monitor the supplier's work, in order to set performance targets and to be able to deal with performance trade-offs. An OEM risks loss of competences through extreme outsourcing to suppliers, since this weakens the understanding of how components are integrated into a system and how to manage system integration. One critical consequence is the decay of architectural knowledge and loss of control over the product performance. Therefore, it is important to acquire and maintain component- and architectural-specific knowledge for the development of complex products (Zirpoli & Becker, 2011).

Furthermore, it has been emphasised by Kalaignanam et al. (2015) that successful OEMs intend to maintain knowledge about the entire product's technology, despite of outsourcing the design of a technology. Similar to the previous paragraph, maintaining a certain level of knowledge also in regard to modular systems facilitates buyers to evaluate supplier suggestions for new designs and technology as well as the ability to assess supplier performance.

Also, the importance of learning and knowledge acquisition is emphasized, which again, contradicts the original mirroring hypothesis according to Sanchez and Mahoney (1996) as the product architecture per se only plays a partial role in shaping inter- and intra-organisational relationships (Becker & Zirpoli, 2011; Zirpoli & Camuffo, 2009) .

The literature review concerning modularity indicates that the focus in recent academics is laid on (1) the impact of product architecture on organisation-related domains and issues, (2) inter-firm coordination and relationship, and (3) the influence of component and architectural knowledge. The dominance of these three aspects within the academic literature suggests a more in-depth review of scientific literature in order to fully grasp these issues respectively.

5. Literature Review on Product Architecture: not Merely a Predictor of Organisational Design

5.1. Product Architecture is Sensitive on Interface Strength

As provided by Ulrich's definition product architecture is characterised by the arrangement and mapping of components within a product to one another. Further, Fixson (2005) describes product architecture as a "comprehensive description of a bundle of product characteristics" (Fixson, 2005, p. 346-347). Product characteristics however, refer to for example the type of components or type and number of interfaces between components. Hence, product architecture entails information on the amount of components and on how these interact with each other. Product architecture can be regarded as a description of the fundamental structure of a product (Fixson, 1995) and specifies, which modules are part of a product system. Further, it specifies the functions of the modules and how they interact with each other, which involves the way they fit together and how the modules communicate with each other (Langlois, 2002). There are four to five different interaction types available (Pimmler & Eppinger, 1994; Sosa et al., 2003), namely *information, energy, spatial, material* and *structure*, of which the first four, the most commonly applied types, will be explained and defined in the data collection and method application section.

The key feature of product architecture is the extent to which the product is modular or integral (Sosa et al., 2007). Thereby, the interfaces *integral* and *modular* represent two extreme ends.

Referring to integral product architecture first, components are in a one-to-many relationship, thus coupled (Ulrich, 1995), which reveals that a change in one component inherently requires a change in another component (Mikkola, 2003). Due to the integrity of the components, enhanced knowledge and interactive learning with high reliance on each other's expertise among organisations and/or teams when designing or developing a product is necessary (Mikkola, 2003). In contrast, a product architecture whose component functions are in a one-to-one relationship (decoupled) is called a modular architecture. According to Gershenson, Prasad, and Zhang (2003), product modularity and product architecture are closely tied to each other because modularity affects the building blocks of a product system. Modular product architectures enable a certain degree of product customisation as flexible platforms allow numerous variations of product compositions through eased disassembling and the re-use of product modules (Gershenson et al., 2003; Mikkola, 2003).

Concluding, it can be stated that the configuration of components embedded in the product architecture infers that: "[…] the degree of modularity inherent in product architectures is sensitive and dependent upon the constituent components and respective interfaces in relation to the system as a whole" (Mikkola, 2003, p. 442).

5.2. Component Coupling Indicates Level of Product Modularity

Most reviewed academic researches (e.g. Brusoni & Prencipe, 2006; Cabigiosu & Camuffo, 2012; Furlan, Cabigiosu, & Camuffo, 2013) associated with product modularity and its related terms are based on the definitions and understandings established by Ulrich (1995), Sanchez and Mahoney (1996), and Langlois (2002), as well as Baldwin and Clark (e.g. Baldwin & Clark, 1994, 2002), and Fixson and co-authors (e.g. Fixson, Ro, & Liker, 2005; Fixson, 2007; Ro, Liker, & Fixson, 2007).

The article by Ulrich (1995) in which he defines product architecture and its corresponding items can be considered as fundamentally important for the understanding of the modularity concept. Product "architecture is the scheme by which the function of a product is allocated to physical components" (Ulrich, 1995, p. 420). More precisely, product architecture is defined as "(1) the arrangement of *functional elements*; (2) the mapping from *functional elements* to *physical components*; (3) the specification of the *interfaces* among interacting physical components" (Ulrich, 1995, p. 420). Ulrich (1995) distinguishes between *modular* and *integral architecture*: *modular architecture* is associated with a one-to-one mapping of the functional elements and the components; hence, *decoupled interfaces*. *Integral architecture* in turn, refers to a complex and non one-to-one mapping from functional elements to physical components; hence, *coupled* component *interfaces*. A modular architecture implies a one-to-one mapping and de-coupled interfaces, which suggests that a change to one component does not require a change in another component, while it is the opposite with coupled interfaces. Modular and integral architectures represent two extreme opposites and are hence rarely the case. However, the product architecture and its degree of coupling of component interfaces determines how and to which extent a product can be changed (Ulrich, 1995). Modular architecture including its de-coupled interfaces enables *product variety*, defined as "diversity of products that a production system provides to the market" (Ulrich, 1995, p. 427).

5.3. Product Modularity as Enabler of Mass Customisation

Modularity has raised attention to the wider public given increased customer demands on more individualised products and the need to react to the fast changing environment. Based on this, product modules enable offering larger product varieties (*mass customisation*) to customers. Hence, it facilitates strategic flexibility on the one hand (Patel & Jayaram, 2013; Salvador, Forza, & Rungtusanatham, 2002; Sanchez, 1995) and builds up strategic firm competences on the other hand (Salvador et al., 2002; Sanchez & Mahoney, 2012).

Mass customisation is understood as means to offer customer product variety (flexibility), based on various modules that can be reconfigured and then produced in relatively large scales, low costs and built-to-order (Kotha, 1995; Piller, 2005; Sanchez, 1999). According to Salvador et al. (2002), it is component swapping modularity, which triggers mass customisation. Modular components are repetitively reconfigured (swapped) on standardised and mass-produced product bodies. Mass customisation and its benefits such as product variety, scale economies and low production costs, can be regarded as a main driver for firms to develop and produce modular products. A popular example of a firm offering mass-customised products is Dell, selling computers based on a variety of modular components selected by customers (Sanchez, 1999). Through modularisation, the US automobile industry also made use of mass customisation in the late 1990s and early 2000s (Ro, Liker, & Fixson, 2007). This, however, led to extensive outsourcing reasoned on the idea that component modularity facilitates design and production independence, due to its one-to-one mapping of elements and components (decoupled interfaces) (Sanchez & Mahoney, 1996; Ulrich, 1995). An industry wide outsourcing trend had the consequence of firms' knowledge decay, missed customer preferences and dependency on few large suppliers (Ro et al., 2007). Further cases underline similar findings, such as the Jeep wiper case by Hsuan (1999) or the Fiat case by Becker and Zirpoli (2011). All cases have in common that despite product modularity, intense buyer-supplier coordination is required, especially for modular NPD (Becker & Zirpoli, 2011; Hsuan, 1999; Ro et al., 2007).

5.4. Product Architecture has Significant Impact on Organisational and Relational Aspects

Newcomb, Bras, and Rosen (1996) emphasise that the product architecture is the governing force in product life-cycle design and higher levels of modularity are recommendable in all life-cycle perspectives. Similar findings underline the influence of product architecture on product design, engineering and sourcing-related decisions. Becker and Zirpoli (2011) for instance indicate that the product architecture can be regarded as a guidance of the way design tasks could be outsourced. Particularly a modular architecture facilitates specialised knowledge about a certain component/part that can be attained by an OEM. Outsourcing design tasks are, however, dependent upon the competencies and knowledge a supplier owns. Hence, the product architecture is (originally) considered as a determinant of sourcing decisions (Becker & Zirpoli, 2011): in-house design and production is suggested when the product architecture is integral, whereas a modular product is recommended to be outsourced. The latter is in association with the idea that a loosely coupled architecture minimises the complexity and uncertainty of the product process as the increased knowledge of a production process enhances the success of a production process. Furthermore, a decreased number of different steps within the process lowers the estimated costs (Fixson, 2005). Also, clearly retrievable production steps of a modular product serve as an incentive for suppliers to deliver high quality components as each function of the component can be located within a final product (Fixson, 2005). Thereby, it is argued that the supplier specialisation and industry structure is reflected in the product architecture; this is for instance recognised in the scheme/structure in which a product is decomposed into subsystems (Becker & Zirpoli, 2011). When a change in the industry occurs, for example a change in the inherent technology of a product, then new boundary decisions need to be taken and organisational engagement regarding learning (by doing) and new competence development is required in order to successfully integrate the capabilities into the systems to attain product performance (Becker & Zirpoli, 2011). It is suggested that firms need a broader set of knowledge about the product and its architecture that in the end results in increased performance (Brusoni et al., 2001). Furthermore, the product's cost structure, perceived strategic value and capabilities inherited within the supply chain (individual processes), as well as the internal costs such as labour and capital costs, and external development costs are predicted to cause changes in the product architecture that affect firm boundaries (Fixson et al., 2005).

Closing, it can be underlined that it is important to have an understanding of the product architecture, when one analyses and defines modularity measures. An understanding of product architecture refers to the product design and design interdependencies, namely the strength of the components (Sosa et al., 2007). In researches involving the analysis of product architecture, the identification of clusters within a system is the primary focus. Analyses of product architecture mostly take place on the product level in which modularity measures consider links of similarity and dependency between the individual components (Sosa et al., 2007). The DSM is a tool that depicts the interdependencies of components and sub-components within product architecture and is often used by academic researches to operationalize systems as well as product architecture (Colfer & Baldwin, 2010 ; Kalaignanam et al., 2015).

6. Firm Integration and Coordination in Relation to Product Modularity

6.1. Level of Firm Integration Dependent on Multiple Factors

There is not an overall exclusive term defining the relationship between buyer and supplier, rather related terms and definitions. Cabigiosu and Camuffo (2012, p. 692) refer to buyer-supplier interactions as "[…] the degree of information-sharing between buyer and supplier". Hsuan in turn uses the term supplier-buyer interdependence, which is defined as: "[…] the degree of supplier involvement in product development leading to capabilities benchmarking, trust development, and creation of inter-firm knowledge" (Hsuan, 1999, p. 202).

In regard to investigating the relationship between product architecture and organisational integration, academics dominantly refer to the mirroring hypothesis. It is argued that the narrow focus on this binary relationship has prevented the view on additional factors as it is assumed that this relationship has a contingent nature (Furlan et al., 2014); hence there is not any clarity of what drives inter-organisation relationships and coordination under the condition of product modularity.

By reviewing the literature in regard to inter-firm coordination in the presence of product modularity, the following dominating aspects are found that influence the degree or the intensity of inter-firm coordination and relationships:

- High levels of product modularity lead to tight and loose inter-firm relationships (e.g. Brusoni & Prencipe, 2001; Cabigiosu & Camuffo, 2012; Cabigiosu et al., 2013)
- Acquisition and learning of (new) capabilities and knowledge through external sources (e.g. Becker & Zirpoli, 2011; Cabigiosu et al., 2013; Furlan et al., 2014)
- Buyer-supplier information-sharing for the means of knowledge retaining, and system integration and performance (e.g. Kalaignanam et al., 2015; Zirpoli & Camuffo, 2009)
- Boundary decision of make-or-buy based on suppliers' capabilities and competences available (e.g. Araujo et al., 2003; Cabigiosu et al., 2013)

- High strategic importance and high pace of technology increase the need to develop and produce items in-house (e.g. Becker & Zirpoli, 2011; Furlan et al., 2014; Takeishi, 2002; Zirpoli & Becker, 2011)

6.2. Component Modularity has Opposing Effects on Buyer-Supplier Relationships

Cabigiosu and Camuffo (2012) found statistical support that high product modularity is associated with a low buyer-supplier relationship. This however, is only valid at the component level with stable architectures involving stability of component technology and loosely coupled components, thus highly modular components (Cabigiosu & Camuffo, 2012). Only if this condition is given, modularity can be regarded as determinant for inter-organisational coordination and relationships in such a way that buyer and suppliers can operate more independently as opposed to buyers and suppliers dealing with tightly coupled components (Brusoni et al., 2001; Cabigiosu & Camuffo, 2012). In addition to this finding, Sosa, Eppinger, and Rowles (2004) claim that modularity has a preventing effect on organisation boundary establishment as modularity may inhibit the alignment between component interfaces interactions across firms. This could be furthermore reasoned by the argument that modularity facilitates switching of suppliers (Hoetker, 2006). Having this in mind, long-term relationships are less likely to be created and firms maintain flexibility in reconfiguring their supply chains (Hoetker, 2006).

Furthermore, Cabigiosu and Camuffo (2012) also underline that product modularity as a result of buyer-supplier co-development requires high-powered inter-organisation coordination mechanisms, even if perfect product modularity is given. A large stream in scientific literature encourages this assumption that modularity leads to tight and intensive inter-firm relationships and requires coordination mechanisms (e.g. Brusoni & Prencipe, 2001; Cabigiosu et al., 2013; Zirpoli & Camuffo, 2009). Increased modularity implies greater division and coordination of tasks that need to be managed across firms (Brusoni & Prencipe, 2001; Cabigiosu et al., 2013). This particularly refers to system integrator firms, whose task is to guarantee product system consistency and performance, and to orchestrate the respective network of various organisations that involve different product development stages from the design to the manufacturing of components (Brusoni & Prencipe, 2001).

6.3. Knowledge Acquisition and Retaining Through Close Inter-organisational Ties

Another aspect that comes along with component modularity leading to tight buyer-supplier relationships is the assurance of keeping certain levels of component knowledge in-house to integrate various systems, and to harness external sources of knowledge, as outlined before (Cabigiosu et al., 2013). Therefore, it can be stated that increasing modularity has two dominating effects: "[…] (i) greater specialisation entailing greater division of labour across firms at the product level, (ii) conscious coordination performed by system integrators at the organisational and knowledge level" (Brusoni & Prencipe, 2001, p. 180).

A case analysis by Hsuan (1999) provides an example of an active supplier involvement in a modular NPD and shows that buyer-supplier relationships can vary from a durable arm's length relationship to a strategic partnership, depending on the type of product in question. Low value and strategically non-important items are usually sourced via durable arm's length relationship and vice versa (Hsuan, 1999). In this case study, the former car wiper had been considered as a standard part, sourced via an arm's-length relationship with its supplier. For the purpose of offering a more customer-friendly wiper, the relationship changed to a closer and more coordination intensive relationship of a modular NPD to achieve improved product performance. Intensified buyer-supplier relationships additionally result in a better system understanding that facilitates cost savings in production and logistics and mutual learning and profitability of which future product generations benefit from. Interestingly, Hsuan's (1999) conclusion is that the type of buyer-supplier relationship impacts product modularisation differently. She argues that firms pursuing an arm's length relationship with their suppliers usually apply it to commodity products such as nuts, bolts and resistors – items that are not considered as the buying firm's core competence. These products then represent open architectures, hence products that are characterised by very few interactions with other components. In turn, closed architecture items, having multiple effects with components and therefore high interface constraints are usually dealt with a strategic partnership.

6.4. Modular Co-development to Ensure System Performance and Development of In-house Capabilities

Similar results are found by Lau, Yam, and Tang (2010), who argue that a (new) modular product design requires buyer-supplier co-development, intensive inter-organisational coordination and information sharing for the means of successful system integration and system performance. Modularity per se does not lead to product performance, only if the product is highly modular. Moreover, product co-development and organisational coordination are positively related to product modularity, based on the argumentation that co-development is more likely to detect and improve problems and to define interface specification in an early stage of product development (Sanchez, 1995).

Both findings furthermore reveal the importance for a buyer and/or assembler to assess external sources for knowledge and innovation acquisition by close buyer-supplier relationships especially in regard to new technologies (e.g. Becker & Zirpoli, 2011; Cabigiosu et al., 2013; Furlan et al., 2014). According to Araujo et al. (2003), the firm's development of capabilities does not occur in isolation but incrementally in constant exchange and relationship with customers, suppliers and other stakeholders. This leads to the selection of suppliers according to the suppliers' capabilities and specialisations.

6.5. Firm's Boundary Decision Partly Depending on the Capabilities Available on the Market

It is argued that firm boundaries are, among other aspects, determined by links and networks a firm has, and the available capabilities on the market (Araujo et al., 2003; Becker & Zirpoli, 2011; Hoetker, 2006). The determination of firm boundaries is a decision that places the own firm's capabilities next to the capabilities that are available in the firm's environment (Araujo et al., 2003). It reveals that the more a firm relies on external sources of supply the more it needs to manage and incorporate these different external capabilities into the own organisational and product systems (Araujo et al., 2003). These kinds of capabilities and knowledge are in line with the assumption as stated by Brusoni and Prencipe (2001, p. 202): "[…]system integrators 'know more than they do'". This corresponds to the idea that the movement of a firm's boundary is not unavoidably asymmetric as vertical integration leads to the advancement of internal expertise and capabilities, but which in turn does not mean that outsourcing leads to declining in-house knowledge of that outsourced item (Araujo et al., 2003). Araujo et al., (2003) refer to *indirect capabilities* of a firm that enable the understanding of the connection of complementary and dissimilar capabilities that exist across firms. Such indirect capabilities enable to interact with other firms, as it is essential to possess capabilities and knowledge also about parts that are outsourced (*know more than they do*). It implies that firms are required to possess a wider range of knowledge and technological capabilities than they practice and produce in-house (Araujo et al., 2003). Hence, boundary decisions and therefore inter-firm relationships are not merely based on the capabilities that the buyer and supplier own.

The literature review of chapter five and six reveal disagreement among scholars concerning the aspect to what extent the product architecture in terms of component coupling influences the need for loose or tight firm integration. Recent literature suggests that the relationship of product architecture and buyer-supplier integration is contingent upon various factors such as capabilities available on the market, learning and knowledge acquisition, and accessing external technologies and innovations. Based on literature findings, the validity of the original mirroring hypothesis is widely questioned among recent academic findings. Therefore, in order to find approval or disapproval for the mirroring hypothesis, the relationship of product architecture (component coupling) and buyer-supplier integration (grey- and black-box development) will be tested by means of the following hypotheses:

Hypothesis 1a: Component coupling is positively related to grey-box development.

Hypothesis 1b: Component coupling is negatively related to black-box development.

7. Component and Architectural Knowledge are Critical Aspects Influencing Organisation's Effectiveness and Efficiency

7.1. Dominant Design Serves as Underlying Concept Explaining Architectural and Component Knowledge

Component and architectural knowledge are often in connection with new product development and innovation as these reveal different kinds of product development. Henderson and Clark (1990) contribute largely to the understanding of knowledge by indicating and explaining the differences between component and architectural knowledge and by providing suggestions for implementations in regard to NPD. As underlined by Henderson and Clark (1990) it is important to distinguish between these two types of knowledge that suggest knowledge related to a) the product as a whole system and b) the product as a set of components (the link between components) in order to successfully develop products. Component knowledge refers to “knowledge about each of the core design concepts and the way in which they are implemented in a particular component” (Henderson & Clark, 1990, p. 11), while architectural knowledge in turn refers to "knowledge about the ways in which the components are integrated and linked together into a coherent whole" (Henderson & Clark, 1990, p. 11).

The concept of knowledge in terms of component and architectural knowledge is based on the concept of *dominant design,* as for instance outlined by Abernathy and Utterback (1978), or Anderson and Tushman (1990). It is argued that organisations establish knowledge and capabilities around existing tasks that are performed. These innovative capabilities are accumulated over time and are therefore organisation-specific and difficult to access by external parties (Henderson & Clark, 1990). A dominant design derives from the organisation's innovative capabilities and refers more particularly to the emergence of a "single product architecture that establishes dominance in a product class" (Anderson & Tushman, 1990, p. 613). Once, such a dominant design has emerged, organisations build around such a stabilised product architecture that is incrementally developed further (Anderson & Tushman, 1990). Incremental development of a product's technologies implies evolutionary and modular change of components within product architecture, as opposed to radical innovation that involve architectural innovation. Based on this idea, a dominant design provides the structure in which components of a product system are allocated. It has however a significant impact on organisational knowledge and management, as the product architecture of a dominant design influences information processing capabilities, information channels and filters, and defines key functional relationships (Henderson & Clark, 1990). To sum up, knowledge about components implies incremental and modular innovation, while architectural knowledge involves radical innovation. The latter is highly challenging for organisations, as architectural innovations do not only change the product to something entirely new, but therewith connected are the underlying organisational designs in terms of management and coordination. In addition to this, the acquisition of architectural knowledge is time and resource consuming, whose learning and adaptability is subtle and difficult to change due to embedded structures and organisational inertia (Henderson & Clark, 1990).

7.2. Architectural Knowledge Specialisation Recommended for System Integrator Firms, Component Knowledge for Specialisation of OEMs

From the section above, it can be derived that the distinction between component and architectural knowledge is critical as it enables a firm to either focus on specified knowledge on components and/or to focus on an entire product system. It is suggested that architectural knowledge is essential to possess in case of system integration, while component specific knowledge is important when it is necessary to identify component interdependencies that enable the adaption of component technologies (Becker & Zirpoli, 2011). It is argued that architectural knowledge is particularly critical for system integrators, such as automotive manufacturers, whereas component knowledge is more important for suppliers and/or OEMs, delivering specified parts and technologies (Becker & Zirpoli, 2011; Takeishi, 2002). System integrator organisations "act as knowledge and organizational coordinators to guarantee the overall consistency of the product and to orchestrate the network of companies involved in the various stages of design and manufacturing" (Brusoni & Prencipe, 2001, p. 185). This implies that system integrators have knowledge in various fields such as product design and manufacturing (Brusoni & Prencipe, 2001). Architectural knowledge is more relevant in regular projects in which firms are required to combine, coordinate and integrate several specialised technologies with organisational mechanisms (Takeishi, 2002). Thus, architectural knowledge is key to system integration. Particularly, modular product architectures facilitate specialisation in product architectures as system integrator and specialisation in components as OEM. This is reasoned by eased allocation of individual parts and access to new technologies, since it is easier to draw from external supply sources (Becker & Zirpoli, 2011).

7.3. Focus on Component and Architectural Knowledge is Depending on the Rate of Change and Newness of Technology

The question of keeping component and architectural knowledge and competences in-house or drawing from external sources is furthermore related to the type and characteristics of the technology in question (Becker & Zirpoli, 2011; Brusoni et al., 2001; Furlan et al., 2014; Takeishi, 2002), and to the technologies that are available on the market (Becker & Zirpoli, 2011).

Scientific literature unambiguously suggests that component knowledge is particularly required when the technology is new and/or is characterised by uneven rates of change (Becker & Zirpoli, 2011; Brusoni et al., 2001; Furlan et al., 2014; Takeishi, 2002). It is argued that organisations should keep knowledge about components in-house in case of rapid change of technology and technological newness in order to acquire new architectural knowledge for the means of (1) system integration (Brusoni et al., 2001; Takeishi, 2002) and (2) the ability to adapt components within a given system (Becker &

Zirpoli, 2011). In case of regular projects and stable technologies, architectural knowledge is more required than component knowledge as the latter is provided by a specified suppliers/OEMs. Knowledge is then partitioned across the buyer and its suppliers (Takeishi, 2002).

Furthermore, the decision to outsource, and therewith-involved decision what levels of knowledge to maintain in-house, is dependent on the competences suppliers own. This is often related to the type of industry, as it is argued that supplier specialisation is mirrored by the industry structure and the evolution of a technology, which is for instance reflected by a product's decomposition into sub-systems (Becker & Zirpoli, 2011).

As a final note it is worth mentioning that it is recommended to keep certain levels of both types of knowledge in-house by direct involvement in design and engineering of components and systems of innovating supplier firms. This facilitates nurturing of knowledge (Becker & Zirpoli, 2011).

7.4. Thick Buyer-Supplier Relationships to Access Innovation and Knowledge are Critical to Maintain In-House Component and Architectural Knowledge

There is an agreement observable among scholars that highlights the importance of tapping into external knowledge and innovation from external sources, particularly from suppliers, which has been furthermore supported by Furlan et al. (2014), and Brusoni and Prencipe (2006). Furlan et al. (2014) for instance underline to maintain certain levels of component and architectural knowledge in-house as system integrator. Both types of knowledge are required to enhance product performance and innovation, radical as well as incremental, which is particularly recommendable if components are outsourced. Therefore, having close buyer-supplier relationships to nurture knowledge is critical in order to access external sources of innovation and/or to retain knowledge about (outsourced) components. In case of the introduction of new technologies, academics suggest to accumulate knowledge for developing in-house component knowledge. This would for example refer to hiring skilled and specialised personnel (Brusoni & Prencipe, 2006), development of design standards by introducing reporting and documenting systems (Takeishi, 2002), and intensive knowledge exchange with suppliers (Furlan et al., 2014).

From this section, it can be stated that both types of knowledge are essential to possess, especially as system integrator/assembler firm that has outsourced modular components. It is critical for firms to balance the two antagonistic forces carefully given the consequences of sourcing decisions, which could result in the decay of component and/or architectural knowledge (Becker & Zirpoli, 2011; Takeishi, 2002). Component knowledge prevents the problem of integrating components into product systems and hence, it avoids costly redesign and re-engineering (Becker & Zirpoli, 2011; Takeishi, 2002). In turn, architectural knowledge is highly important for the understanding of the system and not only an assembler firm should have high architectural knowledge, but also supplier of components should retain certain levels of knowledge about the product's architecture Thus, it is important to keep knowledge about the outsourced tasks at least to some degree in-house, instead of outsourcing the task at the same time with knowledge. This facilitates efficiency and effectiveness of a new product development project (Takeishi, 2002).

7.5. Case Analyses Find Support for Importance of Owning Component and Architectural Knowledge

The case analysis about Fiat provides support for the findings above that modularity (1) leads to two different inter-organisational coordination mechanisms (Becker & Zirpoli, 2011), and (2) underlines the importance to develop and assess external knowledge and innovation for system integration and performance (Becker & Zirpoli, 2011). Extreme component outsourcing resulted in knowledge erosion and consequently ended almost in failure that required fast acting despite the lack of resources. In order to acquire state-of-the-art technology and to regain in-house competences, Fiat built up close relationships with its suppliers to access external knowledge and innovation by the means of learning and knowledge accumulation through joint NPD. Fiat's aim was to develop state-of-the-art engineering competences to design all key systems in-house that directly affect firm performance on the one hand and to outsource standardised components and variant models on the other hand (Becker & Zirpoli, 2011). Following this strategy, Fiat develops two approaches: (1) *template model*: new car development, that intends to incorporate 'a bundle of archetypical' solutions involving all key systems, and (2) *derivate model*: product variance by exploitation of existing systems. These two approaches imply two different buyer-supplier relationships. As template models represent state-of-the art technology, Fiat acquired this knowledge and in the following maintained innovations through intensive collaboration and close ties to the suppliers. Derivate models in turn are outsourced and managed via an arm's length relationship, as these models are adjusted versions of the template models. By introducing this strategy, the so-called *template projects,* Fiat was able to build up architectural and component-specific knowledge by drawing from external sources, and finally benefit from its ability of absorptive capacity. Absorptive capacity is defined as the "capability to […] reconfigure its resource base and adapt to changing market conditions in order to achieve competitive advantage" (Zahra & George, 2002, p. 185), thus, the ability to value, assimilate and apply newly acquired knowledge (Cohen & Levinthal, 1990). Given the primary attention on knowledge acquisition and knowledge retaining Fiat's boundary decision were made based on where to engage in learning in order to attain system integration capabilities (Becker & Zirpoli, 2011).

An article by Ro et al. (2007) finds support for the dominating opinion that modular design requires buyer-supplier involvement in NPD and at the same time this research provides an example in which extreme outsourcing results in high supplier dependency and low overall product performance. Data of this research was selected during a period (2000-2003) when almost all automotive suppliers changed from vertically integrated and integral products to modular products in order to benefit from the advantages of mass customisation. The dependency on the suppliers increased as auto assemblers outsourced much of their previous in-house knowledge. Thereby, the fact was ignored that components and modules can be outsourced completely but still remain at least partly integral to the whole vehicle, such as the cockpit console, which increases the risk of overall declined system performance. Industry-wide, the focus was too high on merely harnessing the benefits of mass customisation, but did not take the customer perspective and preferences into consideration. Difficult buyer-supplier relationships due to the industry wide reliance on few 'mega suppliers', large geographic distances and the focus on cost cutting in the short-term were large obstacles to integrate modularisation within the automotive industry. More interestingly, the findings underline that the modularisation of a former complex and integral product system needs to be thoroughly deliberated in regard to supply chain and infrastructure management. The extreme outsourcing hindered the adoption and adjustment of mass customisation in terms of technology improvement and incorporation of customer preferences. Both, supplier and buyer are required to have a sufficient understanding about the impact modularisation has on the product system and in which way this influences organisational practices and supply chain structures.

The literature findings of chapter seven unambiguously emphasise the importance of knowledge in terms of component and architectural knowledge as a driver of firm integration. It is claimed that component specific knowledge is more relevant for OEMs and for modular products, while assembler firms should own higher levels of architectural knowledge, which in turn is more relevant for integral products (Becker & Zirpoli, 2011; Takeishi, 2002). However, the importance of grey-box development despite product modularity is supported for instance by past experiences, which have shown that extreme outsourcing of modular components increases the likelihood of knowledge erosion, dependency on suppliers and low product performance. But also findings by Cabigiosu et al. (2013) and Zirpoli and Camuffo (2009) underline the importance of firm integration independently from buyer's or supplier's knowledge level and level of product modularity. Therefore, constant information exchange between buyer and supplier are critical especially in regard to NPDs in order to retain and to increase knowledge, and finally, to ensure overall product performance.

Despite the agreement on the importance of retaining sufficient levels of component and architectural knowledge there is no clarity or distinct explanations available in which way component and architectural knowledge drive buyer-supplier integration in relation to product modularity. Therefore, there is a need to test to what extent the following hypotheses can be held as valid in order to identify rules and/or patterns. Clear patterns are provided by Becker and Zirpoli (2011) and Takeishi (2002): component knowledge is more relevant for modular components which can be developed in a grey-box approach, and vice versa; architectural knowledge is more relevant to integral products that can be developed in a black-box approach. Therefore, the following hypotheses can be stated:

Hypothesis 2a: (Supplier) Component knowledge is positively related to black-box development.

Hypothesis 2b: (Supplier) Architectural knowledge is positively related to grey-box development.

7.6. Summary of Literature Review

Concluding, the literature review from chapter five to chapter seven supports the disagreement about the original mirroring hypothesis as a theory applied to explain the relationship between product architecture and organisational integration. Literature findings reveal that loose inter-firm relationships are only possible in case of fully modular and stable product architectures. More dominating is therefore the view that modular products, especially modularity in new product design require high inter-organisational coordination mechanisms and close ties between buyer and supplier, as products, such as automobiles are highly complex. Knowledge in terms of component and architectural knowledge increasingly became subject to recent research projects, due to the high influence knowledge has on firm integration resulting from decisions on which type of knowledge and to what extent a firm should retain in-house or should be outsourced. Either way it is suggested that close buyer-supplier ties and inter-organisational coordination mechanisms are critical in regard to modular product architectures as those enable (1) system integration and product performance, (2) knowledge acquisition and retaining, and (3) access to new technologies and innovation through external sources.

8. Research Methodology: A Qualitative and Quantitative Research Approach

8.1. Qualitative Research as Means of Exploration of a Phenomenon

As stated before, the relationship as depicted in the research model has not been researched yet. This implies lacking empirical, qualitative as well as quantitative data, information and knowledge concerning the impact component/architectural knowledge has on the original relationship between product architecture and buyer-supplier integration. Investigating a phenomenon that is influenced by a particular context and attaining new insights about a phenomenon, (Baxter & Jack, 2008) calls for a qualitative case study. This implies explorative and descriptive questions aimed at developing an in-depth understanding and insight of a subject and/or unique case (Creswell, Hanson, Clark Plano, & Morales, 2007). A case study explores a phenomenon by the means of one or a few cases within a context (Creswell et al., 2007) and is defined as a qualitative approach: "when research has a case bounded by time or place that can inform a problem" (Creswell et al., 2007, p. 241).

Based on this and the formulation of the research question, which is related to a *how* and *why* type of question (Baxter & Jack, 2008), a descriptive and explorative approach is adequate in order to investigate the relationships between knowledge, product architecture and buyer-supplier integration; hence, to discover (new) patterns derived from the analysis of data and theory (Babbie, 2010).

Data collection is primarily conducted by several conversations between the interviewer and respondents. Hereby, interviews, particularly in-depth interviews, are a common technique of data collection in a qualitative research. It is argued that interviews aim at developing a comprehensive understanding and knowledge of an intended research issue (Crouch & McKenzie, 2006). In this research, data collection is conducted by phone interviews that aim at completing the content of the DSM. The direct contact and interaction between interviewer and respondents enables repeated contact to increase validity and reliability, and in turn, justifies the small sample size (Crouch & McKenzie, 2006).

8.2. Combined Methods of Survey Responses and Interviews Enhance Research Quality

While the engineering data collection for the DSM represents the qualitative part of the research, the survey represents the quantitative part. Suppliers' development approach (black- and grey-box) knowledge (component and architectural), supplier capabilities and technological change of products will be conducted by analysing survey responses that have been distributed to ABC's suppliers first qualitatively and in the following, combined with the numerical results of the DSM, quantitatively.

The survey is constructed by Justus E. Eggers as part of his PhD dissertation, with whom this research is in collaboration.

The online survey of the related research work is created according to scientific standards and has been distributed via email that includes a link leading to the survey. A response rate of n = 193 can be regarded as a rate providing relatively valid and reliable outcomes. The survey comprises questions based on the Likert scale, ranging from 1 "strongly disagree" to 5 "strongly agree". Hence, this complies to a pre-coded and uniform standard that is suggested to reduce errors, primarily errors related with coding (Zhang, 2000).

For this research purpose, the survey is examined exclusively on the supplier's component and architectural knowledge, type of product development approach and the control variables. The interviews are aimed at creating the DSM to acquire a full picture of the product architecture as a method to operationalize the variable *product architecture*. The formulas as mentioned in 8.3.1 serve to quantify the DSM outcomes and to implement the aspect of component coupling in the statistical analysis. The statistical analysis will be conducted by applying a multiple hierarchical/stepwise regression, as a commonly used method to capture two-way and multiple-way relationships.

The combined results of these analyses of the DSM and the survey responses intend to find explanations and drivers for the relationship as suggested by the mirroring hypothesis. In particular, the impact of (supplier) knowledge will be investigated as an additional predictor of firm integration. The combination of a case study involving the interviews, and the inclusion of the survey implying a larger set of respondents, are suggested to improve the value of the qualitative research (Gable, 1994). By reviewing the literature, Gable (1994) found out that a qualitative case study in conjunction with a survey enhances generalizability of the study. Gable (1994) summarises that the application of the combined approach in a research establishes contextual richness and further enhances validity by the increased number of findings. In addition to this, Gable points out that it is particularly recommended for business-related researches to include multiple method approaches.

8.3. Operationalization of Variables: Product Architecture, Knowledge, and Buyer-Supplier Integration

8.3.1. Operationalization of Product Architecture in Terms of Component Coupling

In regard to the definition and understanding of product architecture by Ulrich (1995), products are complex systems, as they incorporate a large amount of components with numerous interactions (Cabigiosu & Camuffo, 2012). Hereby, it is distinguished between modular and integral product architectures, which are characterised by tightly coupled and loosely coupled components respectively (Cabigiosu & Camuffo, 2012; Sanchez & Mahoney, 1996; Ulrich, 1995).

The product architecture can be measured in terms of component coupling strength on the one hand and in terms of its relative component coupling strength. In order to measure both, component coupling and relative component coupling the formula (CM) = 1 / (F + I) by Cabigiosu and Camuffo (2012) will be implemented in altered forms:

1. Strength of component coupling C = ∑(incoming interactions + outgoing interactions); an interaction within a cell is defined as 1, while 0 represents no interaction.
2. Relative strength component of coupling C’ = ∑(│relative incoming interactions│ + │relative outgoing interactions│); the ranked interactions (-2 to +2) are added by making use of absolute numbers within each cell.

8.3.2. Operationalization of Buyer-Supplier Integration in Terms of Black-and Grey-Box Development

Firm integration is in association with buyer-supplier information sharing involving the frequency of information exchange (Cabigiosu & Camuffo, 2012), and buyer-supplier interdependence comprising supplier involvement in NPD, as well as trust and creation of inter-firm knowledge (Hsuan, 1999).

While modular products are predicted to allow black-box development, integral products are predicted to allow grey-box development (e.g. Brusoni & Prencipe, 2001). This understanding corresponds to the idea of the mirroring hypothesis (Sanchez & Mahoney, 1996), as modularity reduces the need of close ties in design and production of components (Cabigiosu & Camuffo, 2012). Based on a survey providing scaled data, buyer-supplier integration in terms of the level of black-box and grey-box development will be assessed.

8.3.3. Operationalization of Supplier's Level of Knowledge in Terms of Component and Architectural Knowledge

The level of component and architectural knowledge can be considered as highly subjective depending on the respondent's personal perception (King & Zeithaml, 2003). In literature, there is no example found on how these types of knowledge are measured, as knowledge, and particularly tacit knowledge is difficult to assess and operationalize (Ambrosini & Bowman, 2001). Explicit knowledge of a firm can be found in patents, copyright and other reporting and documenting systems capturing knowledge that have been accumulated over time (Takeishi, 2002). Patents for instance are mostly restricted to industries and do not represent the complete knowledge a firm possesses (King & Zeithaml, 2003). King and Zeithaml (2003) provide an example on how to measure a firm's knowledge. Among other steps, data collection on knowledge through interviews and surveys is involved. For instance, a scale is provided in which managers/respondents are asked to provide their estimates of the competencies their firm has (King & Zeithaml, 2003). Again, the survey distributed to ABC's suppliers provides representative data of the suppliers' level of knowledge and the respective level of component and architectural knowledge. In the survey, there will be a distinction between component and architectural knowledge in order to test the effect of each separately.

9. Measurement of Component Coupling and Data Collection Approach

9.1. Measurement of Interface Strength and Component Coupling by Means of the Design Structure Matrix

Figure three depicts the hierarchical decomposition of a product. From this figure, it can be seen that a modular product can be measured and analysed from (1) *product level*, (2) *system level*, or (3) *component level*. The level of analysis needs to be determined prior to the definition and execution of the research (Sosa, Eppinger, and Rowles, 2007).

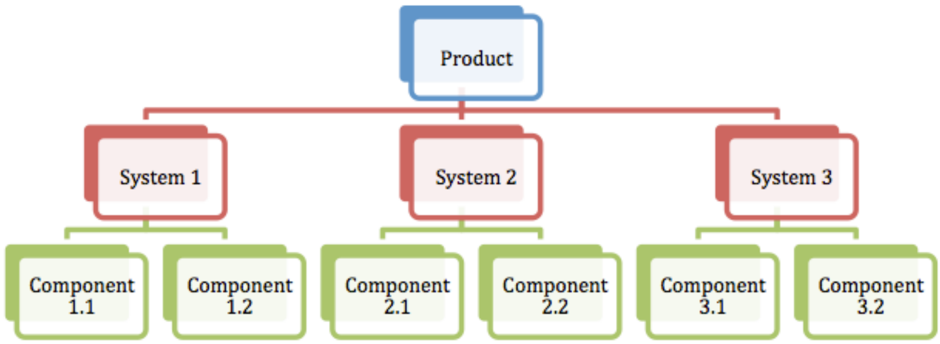

Figure 3 (own image): Hierarchical decomposition of a product (Sosa et al., 2007)

The analysis is conducted at the component level, as the linkages of the respective tractor parts will be subject of the research. The component level is an adequate level of analysis in respect to establishing an understanding for a product's component system, in order to identify how the components function together as modules, and to identify integrative and modular systems (Eppinger & Browning, 2012).

Analysing a complete product architecture (tractor) and its incorporated components can be best conducted by applying the Design Structure Matrix (DSM). The DSM according to Eppinger and co-authors (Eppinger, Whitney, Smith, & Gebala) can be considered as a feasible tool for analysing a product architecture by identifying interdependencies of components and is furthermore one of the most applied techniques and implemented to highlight "the inherent structure of a design by examining the dependencies that exist between its constituent elements in a square matrix" (MacCormack, Baldwin, & Rusnak, 2012, p. 1310). This matrix serves as the identification of interfaces (Cabigiosu & Camuffo, 2012) by means of decomposition and integration and hence, shows the relationship between the respective components (Browning, 2001). The DSM can either be used to illustrate the dependencies of product components or organisational processes (MacCormack et al., 2012).

Originally developed by Don Steward in 1965 and redeveloped by Eppinger and Browning in the 1990s, to-date the DSM is the only existing technique that allows modelling and analysis of a product system by visualising the interactions and interdependencies between components (Eppinger & Browning, 2012). While many of these models, such as Gantt Charts, Critical Path Method, and PERT are capable of illustrating timing, information flows and task interdependencies, they fall short of enabling managers to effectively model and gain a deeper understanding of task interdependencies and iterations in a process. The DSM in turn provides these features and is used to model and manipulate iterative tasks and multidirectional information flows (Yassine, 2007). A further advantage of the DSM over other tools lies in its compactness and its ability to provide a systematic mapping among the elements, which is easy to read regardless of size. Due to the matrix structure, it clearly depicts where interdependencies occur and it facilitates the identification and evaluation of sequencing options (Maheswari, Varghese, & Sridharan, 2006).

There are four types of matrices (see figure 4) for different analysis focuses available, namely *product architecture DSM*, *organisation architecture DSM*, both categorised as static architecture, *process architecture DSM* categorised as temporal flow and the multi-domain DSM including *product, organisation and process DSM* (Eppinger & Browning, 2012).

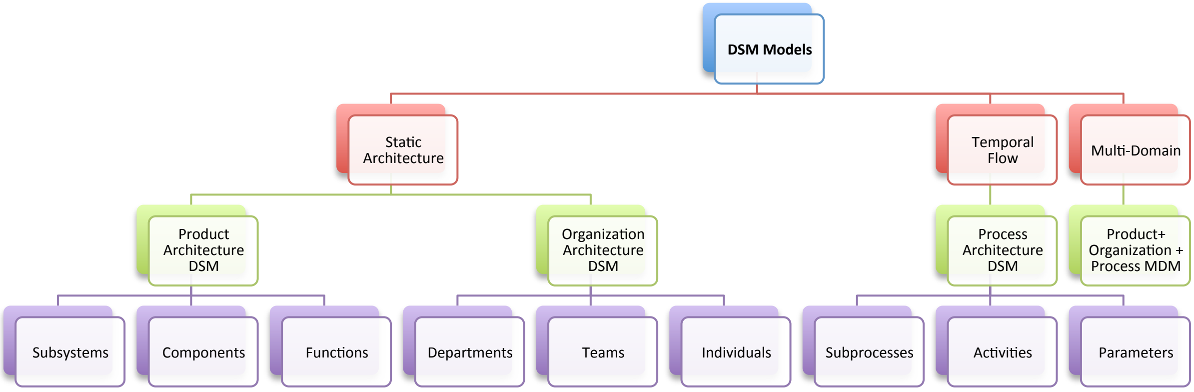

Figure 4 (own image): Four types of DSM models (Eppinger & Browning, 2012)

Static architecture systems refer to product systems "whose elements exist simultaneously" (Eppinger & Browning, 2012, p. 11) with components or team members that physically interact with each other. Temporal flow refers to systems that include elements that actively change over time, such as organisational processes.

Browning (2001) distinguishes between, component-based/architecture and people-based/organisation architecture DSMs within the category 'Static Architecture'. The component-based/architecture DSM is applied to modelling system architectures, which are based on components and/or subsystems and their respective relations and interactions. Team-based or organisation-based DSM in turn refers to modelling processes and activity networks and their respective interactions (Browning, 2001). As can be concluded from the figure and the article by Browning, the product architecture DSM is suitable for the analysis of component interactions as opposed to team-based/organisation or activity-based/process DSM (Browning, 2001, Browning & Eppinger, 2012).

As described above, the product architecture and its degree of coupling of component interfaces determines how and to which extent a product can be changed. Consequently, the degree of interaction between the component interfaces determines the degree of coupling. This implies that there are various types of component interactions. A widely known scheme that distinguishes several types of interactions between components is a qualification scheme according to Eppinger: spatial, energy, information, and material (Yassine, 2004). These interaction types are often in combination with a quantification scheme to weight the interactions of the components relative to each other on a five-point scale (e.g. Browning, 2001; Sosa et al., 2007). As emphasised by Browning (2001) weighting information can be obtained by reviewing architectural diagrams and system schematics, and by attaining knowledge through interviews with engineers and architectural domain experts. Application, definition and explanation are elaborated more detailed in the following method and data collection section.

A so-called hybrid approach of constructing a DSM refers to building and creating a DSM. First, existing documentation is used and then in a subsequent step, experts are involved to complete and validate the initial DSM (Yassine, 2004). This is necessary, as it requires expert knowledge in order to fully capture the dependency characteristics of the components (Maheswari et al., 2006). Capturing knowledge can be achieved for instance by conducting several interviews with experts of certain domains (e.g. product engineers) (Yassine, 2004, 2007). The involvement of experts enables a hierarchical decomposition, namely the identification of components from system-level to sequentially finer component and subcomponent levels. In turn, an unstructured division of components is called non-hierarchical decomposition (Yassine, 2004).

9.2. Data Collection and Method Application

Based on the findings in the previous section, the product architecture of a tractor will be analysed by means of a DSM. Data to create a product architecture DSM in order to analyse the component architecture in regard to *degree of component coupling* and *component interdependencies* is collected by interviewing experts such as product engineers/managers working for ABC. Interfaces can be analysed either within a component system or from an external view, namely across component systems (Sosa et al., 2003). In this study, the latter is the case as the complete product system of a tractor, including its respective components, is relevant to the study.

Above all, the purpose of why the DSM is created should be taken into account in order to conduct an appropriate analysis and derive to the anticipated outcomes (Eppinger & Browning, 2012). Hereby, the DSM intends to depict the product architecture, especially in terms of interface strength of the respective components in order to identify the additional influence of (supplier) knowledge on the relationship between product architecture and buyer-supplier integration in a subsequent step.

Eppinger and Browning (2012) mention two basic steps for building a DSM. Step one refers to the decomposition of the overall product/system into subsystems or components, according to which the rows and columns are labelled. Step two implies the identification of interactions between components and subcomponents. In this step each cell represents these interactions by marks or values.

Having the purpose of the DSM in mind, the following aspects need to be considered according to Eppinger and Browning (2012) in order to create the product architecture DSM:

- *Boundaries*: The limits of the analysed system need to be defined, to include all relevant components and their interactions.
- *Interaction types*: Various types of interfaces, relationships and interactions that exist between components need to be identified, such as physical adjacency of mating parts or flow of materials among subsystems. To indicate the various types of interactions, different marks, values or colours can be used.
- *Interaction strength*: The degree, level or strength of interactions between the components can be depicted by means of a numerical DSM, for instance by the distinction of scaled positive and negative values representing the strength of interactions.
- *Symmetry*: Interactions between components are mostly symmetric, which means that component A interacts with component B and vice versa. Asymmetric interactions refer to components that create noise to another component but the interaction is one-sided.
- *Granularity*: the level of granularity, hence, the appropriate level of detail needs to be considered prior the analysis. It is suggested to keep a manageable size of the DSM that contains approximately 20-50 components.
- *Identifying interactions*: The identification of interactions for the DSM are based on product documentation, interface specification and similar. In addition to the documented information, experts should be consulted in order to capture full and tacit knowledge about a system to verify and validate the DSM.

Furthermore, Sosa et al. (2004) suggest a five-step method to capture fully the product architecture and design interdependencies:

1. *Document product decomposition*: The authors suggest interviewing experts in order to fully capture the product design.
2. *Identify design interdependencies*: This refers to identifying the four different types of interdependencies (spatial, material, information, and energy) and their respective level of criticality according to the weighting scheme (-1, +1, 0, -2, +2).
3. *Construct design interface matrix:* Each cell of the matrix should contain the interface types and their level of dependencies to build up a complete DSM. It is recommended to outline the system boundaries to easily recognise cross-boundary (design) interfaces.
4. *Identify modular and integrative systems*: Identification of larger cross-boundary design interfaces and separation of modular from integrative systems within the matrix is conducted by means of sequencing/clustering.
5. *Highlight critical cross boundary design interfaces*: Previous identified cross-boundary design interfaces can be highlighted to recognise highly critical/ highly dependent interfaces.

Having these two approaches to apply a DSM, a combined approach of Eppinger and Browning (2012) and Sosa et al. (2003 and 2004) will be taken in order to capture the component interactions and interdependencies fully. The following steps are conducted to achieve a complete DSM showing the whole product architecture of a tractor entirely incorporating the interdependencies among the sub-system's components.

9.2.1. Step 1: DSM Construction by Identifying Components and Sub-components

At the beginning of the process, the researcher develops an initial DSM based upon documents, such as product information brochures and similar, which are provided on the website of ABC. In addition to these documents, construction publications of certain parts such as the front axle are included. Furthermore, scientific publications concerning vehicle components, and in particular researches applying the DSM in the automotive industry (Cabigiosu & Camuffo, 2012; Cabigiosu et al., 2013; Kalaignanam et al., 2015) have been reviewed in terms of component level and component content. On basis of this initial DSM, the content of the DSM has been discussed in several phone meetings involving the researchers and consulted experts owning general knowledge of the tractor. Three different experts were involved separately in the process of the DSM construction. Having the content of the DSM completed, a 62x62 DSM has been created incorporating 21 main components (component level 1) and its respective sub-components (component level 2).

These steps of the DSM creation are in line with (1) *document product decomposition* according to Sosa et al. (2003) and the determination of *boundaries* and *granularity* as described by Eppinger and Browning (2012).

9.2.2. Step 2: Identification of Design Interfaces and Interdependencies in Terms of Interaction Types and Strengths

Prior to the completion of the DSM, the DSM has been pilot tested by one of the three consulted engineers. This engineer tested the DSM in regard to its content (listed components) and the time needed. This engineer focused on filling in the lower part, more precisely, the section below the separating diagonal by exclusively considering the vertical line representing the incoming interaction. The decision to test merely the lower part of the DSM is based upon the large size, the substantial amount of time needed to fill in each cell, and the possibility to deliberate on all included components of the DSM. The DSM itself has been regarded as correct and complete in terms of its incorporating components. However, the large amount of time that is required to fill in the DSM was a major concern. Therefore, it was decided to leave out the second level of the engine as a large, independent component system and given the fact that this component system is sourced as a complete part. Further, the DSM has been split into four parts to reduce the time for the following engineers, who fill out the DSM. After pilot testing and adjusting the DSM, four further engineers / domain experts have been asked individually to complete one of the four matrix parts in a 60-minutes phone meeting. As the lower part of the DSM has already been completed in the test, the four engineers focused on completing the upper part by merely considering outgoing interactions (horizontal line). However, they checked the lower part of their section in order to confirm the correctness of the first engineer. Prior the interviews a short guideline describing the application of the DSM has been sent to the engineers. Further questions are solved during the phone meeting. Here, consistency of answers and a complete and correctly filled-in DSM are highly important and are achieved by including and considering these elements and aspects:

The engineers were asked to identify for each component (a) interaction type, and (b) interaction strength. This complies to step 2 by Eppinger and Browning (*identify design interdependencies*) and step 3 (*construct design interface matrix*) by Sosa et al. (2003).

The table below summarises 1) a definition for each interaction types as provided by Pimmler and Eppinger (1994) (left column), 2) verbal description for each interaction strength (middle column), and 3) definition of interaction type assigned to interaction strength (right column) (Cabigiosu et al., 2013; Pimmler and Eppinger,1994).

Interaction Type	Interaction Strength	Definition of Interaction Type and Strength
Spatial: Identification of needs for adjacency or orientation between two elements, e.g. physical adjacency, alignment, orientation.	Required (+2): Desired (+1): Indifferent (0): Undesired (-1): Detrimental (-2):	Physical adjacency is necessary for functionality. Physical adjacency is beneficial, but not absolutely necessary for functionality. Physical adjacency does not affect functionality. Physical adjacency causes negative effects but does not prevent functionality. Physical adjacency must be prevented to achieve functionality.
Energy: Identification of the need of energy, e.g. heat, vibration, electricity.	Required (+2): Desired (+1): Indifferent (0): Undesired (-1): Detrimental (-2):	Energy transfer is necessary for functionality. Energy transfer is beneficial, but not absolutely necessary for functionality. Energy transfer does not affect functionality. Energy transfer causes negative effects but does not prevent functionality. Energy transfer must be prevented to achieve functionality.
Information: Identification of need for e.g. signals, controls, transfers.	Required (+2): Desired (+1): Indifferent (0): Undesired (-1): Detrimental (-2):	Information exchange is necessary for functionality. Information exchange is beneficial, but not absolutely necessary for functionality. Information exchange does not affect functionality. Information exchange causes negative effects but does not prevent functionality. Information exchange must be prevented to achieve functionality.
Materials: Identification of the need for information	Required (+2): Desired (+1):	Materials exchange is necessary for functionality. Materials exchange is beneficial, but not absolutely necessary for functionality.

or signal exchange materials exchange between two elements, e.g. air, oil, fluids, flows.	Indifferent (0): Undesired (-1): Detrimental (-2):	Materials exchange does not affect functionality. Materials exchange causes negative effects but does not prevent functionality. Materials exchange must be prevented to achieve functionality.

Table 1 (own image): General quantification scheme of four interaction types (Browning, 2001; Sosa, Eppinger & Rowles, 2003)

These four interaction types (spatial, energy, information and materials) are identified as the mostly applied types in scientific research (e.g. Browning, 2001; Cabigiosu & Camuffo, 2012; Cabigiosu et al., 2013). The dominance of these four types in empirical studies can be considered as sufficient to entirely capture the components' and sub-components' interactions. Since the goal is merely to acquire an overall overview of the product architecture for the means of further analyses in regard to knowledge (component and architecture) and buyer-supplier integration, further interaction types could, again exceed the scope of the research purpose and would create a too complex matrix.

Component coupling is measured on a five-point scale as suggested by (Browning, 2001) and applied in various researches that have implemented the DSM (Cabigiosu & Camuffo, 2012; Sosa et al., 2003; Sosa, Eppinger, et al., 2007). Different types of scales such as 0 to 1, or 1 to 9 are also implemented to represent the dependency strength (Maheswari et al., 2006). Nevertheless, the advantage of this qualification scheme as depicted in the table is able to capture positive and negative (inter)dependencies, hence components that either hinder or enhance the component's functionality. A zero level (0) indicates an indifferent effect; there is no effect on functionality. (-1) and (+1) represent a weak effect negative or positive on functionality, while (-2) and (+2) depict a strong effect.

For each component, the relationship to every component in the matrix will be evaluated in terms of strength and type of interaction. Within a matrix cell, each corner represents another type of interaction (figure 5). Instead of the initial letters of the respective types the interface strength (-1, +1, 0, +2, -2) is assigned. For instance, component *A* has the following interaction with component *B*: spatial = 0, energy = -2; information = +1, materials = +2. A blank cell implies that there is no interaction between the components at all. The structure of a cell is depicted below by figure 5. This is conducted for each cell; identification of interaction types and their respective levels of criticality (Sosa et al., 2003).

Spatial 0	Energy -2
Information +1	Materials +2

Figure 5 (own image): DSM component cell including type and strength of coupling (Pimmler & Eppinger, 1994)

Within this step, which refers to the identification of design interdependencies and the construction of the DSM, the asymmetric and symmetric nature of the components are captured at the same time by asking how a component depends on another one. It is assumed that asymmetry can be found in hold and support functions of components. Sosa et al. (2003) provide the example of a frame of a gearbox that depends structurally on the weight of the gears to support, but not vice versa. Furthermore, design interdependencies could be asymmetric due to functional reasons.

9.2.3. Step 3: Analysis and Interpretation of DSM

The static DSM, also called N^2, is a square matrix that enables the analysis of product systems/product architectures. This particular DSM is a component-based architecture, as identified above, which is used to model system architectures based on components and sub-components (Browning, 2001; Yassine, 2004).

After building the DSM, a subsequent step is the analysis and interpretation of the DSM. For doing so, it is significant that the matrix is created und understood correctly: the order of components needs to be exactly the same in the first horizontal line and vertical line (Browning, 2001; Eppinger & Browning, 2012). In the matrix, each component in the columns is dependent on a component in the horizontal line. It needs to be distinguished that the components below the diagonal line are dependent on a component activity that has been produced prior. In turn, the interdependencies indicated above the diagonal represent component activities that have yet to be produced (Austin, Baldwin, Li, & Waskett, 2000):

- The vertical line represents *depend* – a component is dependent on a previous component's activity, hence reading across an element's line reveals its input sources (incoming interactions).

- The <u>horizontal line</u> represents *provide* – a component provides activity/information to another component; hence reading down an element's column reveals its output sources (outgoing interactions).

(Browning, 2001; Danilovic & Browning, 2007; Sosa et al., 2003).

PROVIDE

	A	B	C	D	E	F	G	H	I
A									
B	X		X	X		X		X	X
C	X	X			X	X		X	X
D	X	X			X		X	X	X
E	X		X	X			X	X	X
F		X	X						
G				X	X				
H		X	X	X	X				
I	X		X		X				

DEPEND

Figure 6 (own image): Simplified example of DSM (Browning, 2001)

This simplified example of a DSM (figure 6) by Browning (2001) shows that element B provides an activity to element A, C, D, F, H and I, while element B is dependent on a previous activity by element C, D, F and H.

Interactions and the relative strength of interactions will be calculated in two separate steps, following the two formulas as explained in chapter 8.3.1.

For these two calculations two new excel sheets will be created with a DSM showing (1) presence of interactions and (2) the relative strength of each coupling, both for incoming and outgoing interactions.

9.3. Potential Solutions to Obstacles Related to the DSM Application and Analysis

During the process of collecting the data and content of the DSM, several errors and obstacles could occur that possibly lower the quality of the data and are therefore highly critical to the research and its results. Given the criticality and dependency on involving expert knowledge in the construction and data collection processes these steps are subject to misunderstandings and misinterpretations, but also disagreements among the experts.

Two engineers will be consulted separately via a phone conference in order to construct the DSM and to agree on an appropriate component level. As both phone conferences take place separately and on different days the consulted experts could have different opinions on which components should be included in and/or excluded from the DSM. As two experts are consulted for the construction of the DSM contradicting opinions on the content are possible. In advance this has been attempted to be avoided by involving experts that are on the one hand own general knowledge about the tractor construction, but on the other hand have specialised knowledge about a certain system. In case two different opinions on several components occur a third expert could be consulted to particularly decide upon the inconsistencies.

Similar could happen in the course of the interviews, when engineers/experts are asked to fill in the component interdependencies and component coupling strengths. Again, different outcomes are likely that could be an obstacle to correctly interpret and analyse the DSM. In this case, it is advised to involve an odd number of engineers (e.g. 3, 5, or 7) to control for interaction types and/or strengths that are mostly chosen. If the data of one or a few components provided by the engineers differs completely, an additional expert could be involved and asked about his opinion. In regard to types of component interdependencies, not only disagreement among the experts could occur but also that none of these types adequately represents the interdependence of one or two components with other components. In order to avoid confusion and ensure consistency of the DSM data collection, it will be asked to choose a type of interaction, which is closest to the expert's perceived type of interaction.

Colour schemes represent the respective level of component interactions and strengths in order to depict tendencies of modular and integral components. This is particularly important for the final results of the research, given the assumption that the degree of modularity influences the degree of buyer-supplier integration.

As mentioned in more detail in the research methodology section, errors due to misunderstandings and misinterpretation could occur during interviews/conversations. This is especially the case for phone conferences in which the DSM content has been discussed, for instance, when phone connections were occasionally unclear. The participation of four parties at each phone conference ensures that the suggestions made by the expert are fully understood and correctly applied on the matrix. Further, the guideline and a brief introduction to which questions regarding the DSM are solved ensure the correct application of the DSM.

10. Qualitative Analysis of DSM and Supplier Survey

This chapter is hidden due confidentiality reasons.

11. Quantitative Analysis by Means of a Multiple Regression Analysis

11.1. Main Variables of Analysis: Development Approach, Knowledge, Component Coupling and Control Variables

From the statistical analysis it is desired to find support for the assumption that component and architectural knowledge can be considered as an additional driver of buyer-supplier integration, which consequently rejects the idea of the mirroring hypothesis. The literature review of component and architectural knowledge deriving to the following conclusions:

Architectural Knowledge	Component Knowledge
• Focus on entire product system • Useful for system integrator firms • Related to radical innovation • Stable product technology, and regular product projects • Refers to higher levels of integral products • Grey-box development	• Focus on individual component • Useful for component suppliers • Related to incremental innovation • Product characterised by fast change of technology, and new projects • Refers to higher levels of modular products • Black-box development

Table 3 (own image): Summary of literature findings about architectural and component knowledge

Based on the literature findings a correlation can be expected between 1) architectural knowledge, low component modularity and grey-box development, and 2) component knowledge, high component modularity, and black-box development. Control variables will be included to assess the strength relationship of knowledge and product architecture as predictor of buyer-supplier integration. It assumed that *technological change* has an impact, as mentioned in the table above; keeping knowledge about component(s) in-house if technology changes rapidly to react instantly, while for stable technology and regular projects architectural knowledge is more important, as specified knowledge is owned by supplier/OEM, who delivers a particular component. Furthermore, *supplier's capability* of information processing and innovation/development is identified to have an impact on the buyer-supplier integration and type of knowledge. Suppliers can serve as source of innovation and access to new technologies. The selection of a supplier often depends on the capabilities it has in regard to specifies technologies. The relationship between buyer and supplier is considered as having an effect on buyer-supplier integration in particular. This aspect is related to the supplier's perspective on the relationship to ABC. Based on the literature findings it can be derived that a positive perception of the relationship to ABC has an equally positive effect on information sharing, access to technology and overall, on the closeness of buyer-supplier integration. Hence, the *customer status* of ABC is the third control variable.

11.2. Multiple Regression Analysis with Mean-centred Main Variables and Interactions Variables

A multiple regression analysis is applied, conducted in a hierarchical / stepwise manner to capture the influence of each variable (Dawson & Richter, 2006).

The main assumption as depicted in the research model is that buyer-supplier integration in terms of black- and grey-box (Y_1, Y_2) is not merely predicted by the product architecture in terms of strength of component coupling (X_1), but also (supplier) knowledge in terms of component and architectural knowledge (X_2).

As a first step the constructs of each variable (component and architectural knowledge, and grey- and black-box development) is averaged and labelled (Hofman, Halman, & van Looy, 2016).

As a subsequent step, the interaction variables (X_1 and X_2) and control variables were aggregated and mean-centred in order to avoid multicollinearity that is in relation to multiple regression (Dawson, 2014; Jaccard, Wan, & Turrisi, 2009). Jaccard et al. (2009) argue that a standardised format in which all variables are standardised as the Z score is not adequate for multiple regression; hence an unstandardised solution is suggested via mean-centring all independent variables (but not the dependent variable).

In the following a stepwise/hierarchical regression analysis is applied by making use of the program SPSS 23 by IBM to test the effects of component coupling (X_1) and component knowledge (X_{2a}) and architectural knowledge (X_{2b}) on the dependent variable buyer-supplier integration in terms of grey-box development (Y_1) and black-box development

(Y_2). In line with the regression formula: $Y = b_0 + b_1X_1 + b_2X_2 + \varepsilon$ (Dawson, 2014), the analyses will be conducted as follows:

11.2.1. Regression analysis 1

Dependent variable: Grey-box development (Y_1)

Block 1: Control variables (technological change, supplier capabilities, and customer status)

Block 2: includes centred variable of component coupling (X_1) and supplier component (X_{2a}) and architectural knowledge (X_{2b})

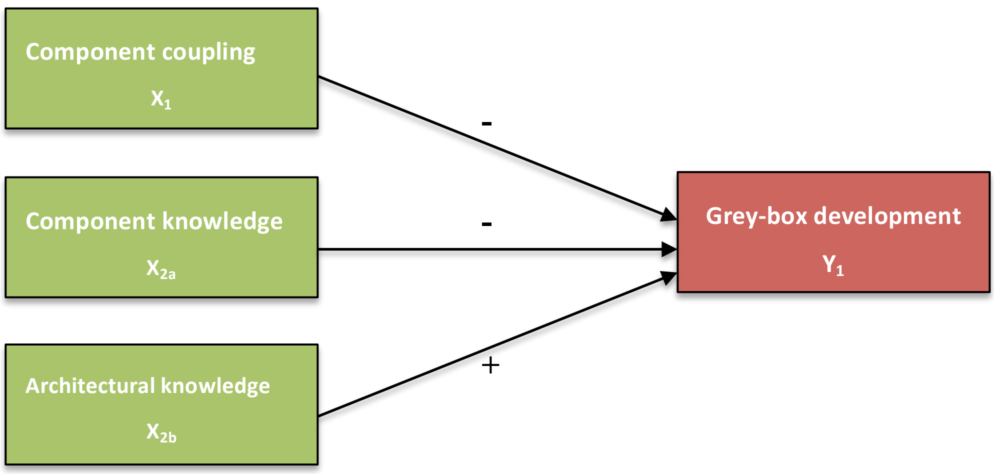

Figure 9 (own image): Model of regression analysis 1

11.2.2. Regression analysis 2

Dependent variable: Black-box development (Y_2)

Block 1: Control variables (technological change, supplier capabilities, and customer status)

Block 2: includes centred variable of component coupling (X_1) and supplier component (X_{2a}) and architectural knowledge (X_{2b})

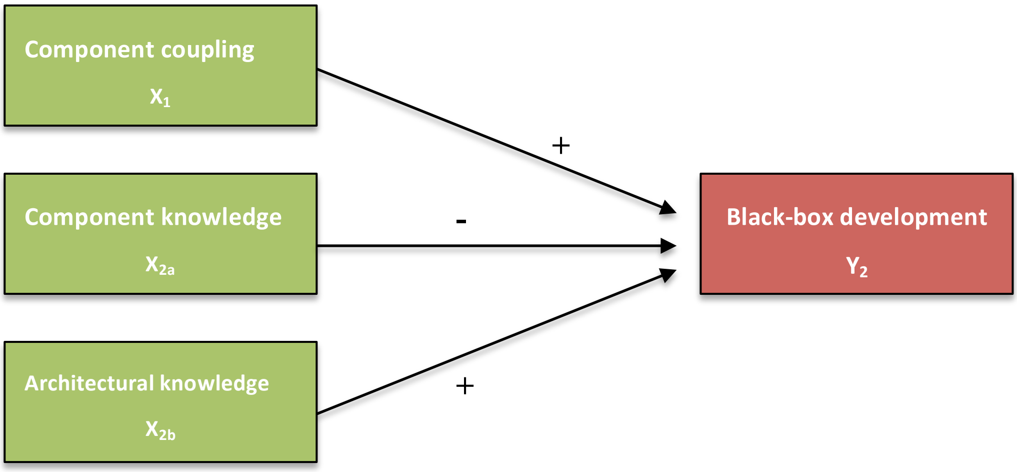

Figure 10 (own image): Model of regression analysis 2

11.3. Statistical Results Show Rejection of Hypotheses

11.3.1. Test 1: Prediction of Grey-Box Development by Component Coupling and Architectural and Component Knowledge

A predictor of multicollinearity is VIF (Variance Inflation Factor). A rule of thumb suggests that VIF values should be below ten in order to be within the acceptable threshold. Here, VIF values range from 1.081 to 2.477, hence below the recommended threshold of 10 (De Veaux, Velleman & Bock, 2012; Kock & Lynn, 2012).

These regression results are related to H1a and H2a, testing the effect of component coupling (H1a) and component and architectural knowledge (H2a) on grey-box development. Although this test in non-significant, which can be particularly seen at the ANOVA significance values ($ANOVA_1$ sig = 0.248 > 0.05; $ANOVA_2$ sig = 0.117 > 0.05), there are significant correlations between component coupling ($p = 0.013$), supplier capabilities ($p = 0.041$) and supplier component knowledge ($p = 0.038$) and grey-box development recognisable. In particular component coupling shows exclusive and significant impact on grey-box development as unique variable within the model, as can be seen in the coefficient table ($p = 0.033$; $\beta = 0.292$).

However, based on the non-significant ANOVA values H1a and H2a are rejected.

11.3.2. Test 2: Prediction of Black-Box Development by Component Coupling and Architectural and Component Knowledge

VIF values range from 1.081 to 2.271, hence below the recommended threshold of 10.

These regression analysis results are related to H1b and H2b testing the effect of component coupling (H1b), and component and architectural knowledge (H2b) on black-box development. Component knowledge ($p = 0.001$), architectural knowledge ($p = 0.024$) and supplier capabilities ($p = 0.014$) are significantly correlated to black-box development. Although the ANOVA statistics remain non-significant in the second model ($p = 0.063 > 0.005$) indicating a rejection of H1b and H2b, there is an increasing R Square value from 0.090 to 0.205, which reveals that the second model (includes all variable) accounts for 20.5% of the variance. Further, component knowledge is the only variable within the complete model that has a significant impact on black-box development ($p = 0.039$; $\beta = 0.397$).

Based on the findings, H1b and H2b are both rejected.

12. Analysis of Qualitative and Quantitative Results

12.1. Analysis of Quantitative Findings: Despite Rejection of Hypotheses, Statistical Results Reveal Interesting Outcomes

On basis of an extensive literature review, these four hypotheses were developed and tested by applying a multiple stepwise/hierarchical regression analysis:

- H1a: Component coupling is positively related to grey-box development.
- H1b: Component coupling is negatively related to black-box development
- H2a: Component knowledge is positively related to black-box development.
- H2b: Architectural knowledge is positively related to grey-box development.

Although, the expectations are not met as these hypotheses are rejected, results still derive to interesting findings:

Expected Literature Findings	Actual Statistical Findings
• High component coupling is positively related to black-box development • Low component coupling is positively related to grey-box development	• High and low levels of component coupling are (positively) related to grey-box development
• Component knowledge is more likely to be owned by suppliers (OEMs) • Architectural knowledge is more likely to be owned by buyers (system integrators)	• Suppliers own higher levels of component knowledge than architectural knowledge
• High levels of component knowledge is more likely to lead to black-box development • High levels of architectural knowledge is more likely to lead to grey-box development	• High component knowledge is associated with grey-box development • High architectural knowledge associated with black-box development • High architectural and component knowledge is associated with black-box development

Table 4 (own image): Summary of expected literature and actual statistical findings

The statistical outcomes show largely contradicting results to the expectations made on basis of the literature review (see table 4). The hypotheses were formulated according to the understanding of the mirroring hypothesis; a support of findings would therefore confirm the mirroring hypothesis, whereas a rejection of the hypotheses questions its validity or indicates a non-sufficient theoretical approach. The most distinctive results are the dominance of grey-box development independently from the level of component coupling, and the dominance of component knowledge that ABC's suppliers own. The latter point is consistent with literature findings.

Opposing to the hypothesis, there is not any statistically significant relationship found between the level of component coupling and black-box development. Interestingly, black-box development is correlated to architectural knowledge, and to architectural and component knowledge, while there is no correlation found between black-box development and component knowledge. This indicates that suppliers are likely to develop products independently, if they had the knowledge of the complete (final) product and/or component system.

Despite these outcomes, there are not any clear rules or patterns observable providing an explanation of how the product architecture predicts buyer-supplier integration with consideration of the knowledge aspect, as expected from the identified literature findings. The rejection of the hypotheses and hence, the rejection of the assumptions and findings that were made by scholars, underline the complexity and contingent nature of the relationship between knowledge, product architecture (component coupling) and buyer-supplier integration.

Noteworthy mentioning is the detrimental effect of the control variables, which are all non-significant in relation to any of the independent and dependent variables – except of supplier capabilities, which is closely related to knowledge. The second regression model test, which includes the main variables, shows increased significance of ANOVA statistics, increased R Square value, and the significant F change value becomes smaller (hence, closer to a significant value). Although still non-significant, these results indicate that the control variables are not suitable for the model, while the main independent variables indeed show significant correlations with the dependent variables.

12.2. Discussion of Findings Reveal the Importance of Firm Knowledge and the Minor Role of Product Architecture

As mentioned in the previous section, the most distinct results are the positive relationship of supplier's level of component knowledge and grey-box development, and the positive relationship between component coupling and grey-box development. The dominance of grey-box development, hence tight buyer-supplier integration is not only indicated by the quantitative analysis and but also recognized in the qualitative analysis. This outcome corresponds to scientific findings underlining the importance of close buyer-supplier integration in regard to collaboration and information exchange. This is especially important for NPDs where successful system integration of the new component is key to both, buyer and supplier (e.g. Brusoni & Prencipe; Cabigiosu & Camuffo, 2012; Cabigiosu et al., 2013; Takeishi, 2002; Zirpoli & Camuffo, 2009). Cabigiosu et al. (2013) and Zirpoli and Camuffo (2009) even claim that firm integration by means of constant information exchange should be present independently of buyer's and/or supplier's level of knowledge and the constituent product architecture. The survey and thus, this study refer to the development of components as opposed to already existing components. Based on this, literature findings reveal exemplary cases in which the importance of buyer-supplier integration is critical in a NPD (e.g. Fiat case by Becker and Zirpoli, windshield development by Hsuan, A/C system by Zirpoli and Camuffo. In case of integral Sosa et al. (2007) as well as modular NPD (Brusoni & Prencipe, 2001) high-powered inter-organisational coordination mechanisms are especially needed in order to ensure system performance and to avoid costly reengineering (Takeishi, 2002; Ulrich, 1995). This study provides an additional support stressing the importance of firm integration as particularly relevant in NPDs, whereas the level of firm integration is not dependent on the product architecture of the component. Since the quantitative results signify a positive correlation between component coupling and grey-box development, there is however an indication that increased component coupling of a NPD enhances the importance of firm integration, whereas the opposite is not confirmed (low component coupling predicts black-box sourcing). This furthermore highlights the significance of firm integration during a new product development process.

The quantitative and qualitative results show predominance of component knowledge over architectural knowledge. This is supported by the literature findings that suggest that knowledge in terms of component and architectural knowledge clearly plays a major role in shaping firm boundaries (e.g. Araujo et al., 2003; Cabigiosu et al., 2013). “It is not the products that design organizations. Knowledge does” (Brusoni & Prencipe, 2006, p. 186) stresses the impact knowledge has and at the same time the minor role of product architecture. The predominance of suppliers’ component knowledge is complying the expectations made, reasoned by their role as OEMs that have specified knowledge of particular components. The positive relationship between component knowledge and firm integration can be reasoned by the supplier’s competences and capabilities (e.g. Araujo et al., 2003; Cabigiosu et al., 2013), and the buyer’s intention to access new technologies, and to nurture and/or retain component specific knowledge (learning and knowledge acquisition) (Becker & Zirpoli, 2011; Zirpoli & Camuffo, 2009).

Particularly recognised in the qualitative analysis (table 3) is the marginally lower level of architectural knowledge, indicating a high system and component knowledge by the suppliers. Applying to buyers and suppliers equally, there is a general agreement among scholars, who suggest to retain sufficient knowledge of the product’s components and architecture to avoid knowledge erosion and dependency on supplier, enhance performance, and to realise radical and incremental innovation (Becker & Zirpoli, 2011; Furlan et al., 2014). Corresponding to “firms know more than they do” (Brusoni & Prencipe, 2001, p. 202), it is argued that firms outsource parts and components because of task partitioning, for instance due to lacking capacity as opposed to lacking knowledge. This aspect refers to the concept of dependency on capacity and dependency on knowledge, established by Fine and Whitney (1996). Furthermore, the level of knowledge and therewith-related make-or-buy decisions is among other aspects contingent on type of technology, market availability, and pace of technological change (e.g. Becker & Zirpoli, 2011; Stefano Brusoni et al., 2001; Furlan et al., 2014; Takeishi, 2002).

In contrast to the hypothesized expectations is the outcome of the positive relationship between architectural knowledge and black-box development, and that architectural and component knowledge (both combined) are positively related to black-box development. Neither product architecture nor architectural knowledge show any significant correlation with grey-box development. These results indicate that knowledge of the product's components and in particular about architecture enable the supplier to develop a component by applying a black-box approach.

Architectural knowledge is related to radical innovation, a capability that is particularly difficult to access, as this capability incorporates more than the exclusive understanding of a product architecture system. Rather, innovative capability is embedded in the entire organisation implying uniqueness and competitive advantage, but also inertia in relation to changes (Henderson & Clark, 1990). Architectural knowledge as driver of black-box development therefore signifies specified technology that enables or also forces (due to uniqueness of technology) the supplier to develop a product in-house.

A further explanation for this outcome is provided by (Zirpoli & Camuffo, 2009), who argue that black-box development (of modular NPDs) is only possible if the component is defined and specified ex ante by the OEM that owns high component and architectural knowledge. In turn ex post defined and specified components require tight buyer-supplier coordination. In addition to these conditions, researchers argue that black-box development requires stability of the project and component life (stable technology and environment), and independent coupling and de-coupling (full component modularity) (Brusoni et al., 2001; Cabigiosu & Camuffo, 2012; Cabigiosu et al., 2013; Fixson, 2005). In particular referring to product architecture stability and full component modularity, Ulrich mentions that fully modular and integral products represent two extreme ends and rarely exist in real life. The DSM underlines the complexity of a complete product, which can be considered as technologically advanced and with numerous component interactions. Consequently, exclusive black-box development especially in a NPD is barely possible independently from the product architecture (Cabigiosu & Camuffo, 2012).

12.3. Conclusion: Rejection of Mirroring Hypothesis

Findings unambiguously reject the simplistic idea of the mirroring hypothesis and highlight the importance and the impact component and architectural knowledge have on the level of firm integration. Moreover, there is indication that product architecture plays a rather minor role in shaping inter-firm coordination and collaboration (Becker & Zirpoli, 2011; Zirpoli & Camuffo, 2009). Moreover, the relationship as suggested by the mirroring hypothesis can be considered as highly contingent (Furlan et al., 2014), since multiple characteristics related to the product and component, market and industry and internal firm related aspects need to be taken into account when making decisions upon firm integration. High contingency is furthermore related to decisions concerning the product architecture, as this is similarly influenced by multiple factors, such as the industry structure, which mirrors product architecture (Becker & Zirpoli, 2011).

Statistical evidence suggests that increasing component coupling increases the need for grey-box development, while there is not a relationship found between component coupling and black-box development, supporting the assumption that component coupling per se cannot be regarded as a predictor of buyer-supplier integration. Generally, constant information exchange and collaboration are required in a NPD. This refers to both, modular and integral components. In case of modular components, it is suggested that ex post specification and definition of the components increase the need for firm integration while ex ante specification and definition decrease the need for firm integration (Cabigiosu & Camuffo, 2012). The tractor architecture as depicted in the DSM shows numerous component interdependencies with various degrees of component strengths, which in turn lead to the conclusion that pure black-box development is barely possible, at least for component systems at level one and two.

The visualisation of a complete product architecture including its component interdependencies depicts the complexity of a tractor and furthermore gives an impression of where the critical interdependencies in terms of many versus a few, and strong versus weak component interdependencies are. Clearly distinctive become also the interactions of subcomponents within a component system such as transmission or hydraulics, although merely depicting component level one and two. Therefore, findings suggest that the complexity of a product increases the need for grey-box development at least in regard to system integration and performance, and in case the supplier's architectural knowledge of the final product is insufficient.

Concluding it can be stated that research underlines the importance of joint development, collaboration and integration of buyer and supplier in relation to NPDs of complex product systems. Supplier knowledge is a critical aspect influencing the development approach and in turn, the level of buyer-supplier integration. These results show that the relationship between product architecture and buyer-supplier integration is highly contingent, clearly insufficiently represented, and overly simplified by the mirroring hypothesis. (Supplier) Component and architectural knowledge are found to have significant impact on buyer-supplier integration. Furthermore, this research underlines that the impact of knowledge is even more dominant than the product architecture in case of a complete and complex product architecture. Below (figure 11), the identified main drivers of black- and grey-box development are summarised (AK means architectural knowledge; CK means component knowledge).

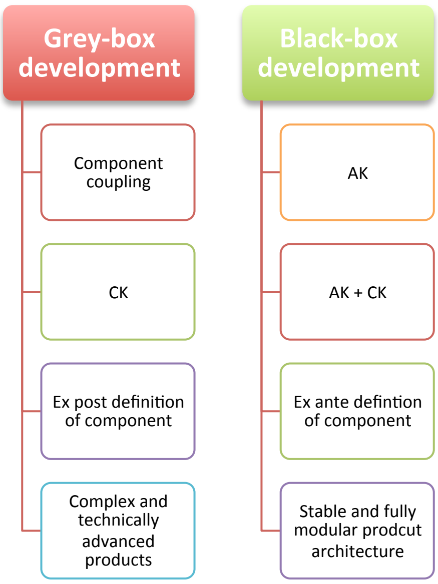

Figure 11 (own image): Drivers of grey- and black-box development

12.4. Relevance of Findings and Scientific Contribution

Research is aimed to provide a more generic view on the relationship between product architecture and buyer-supplier integration with consideration of the knowledge aspect. Indeed, knowledge has a significant impact and in addition to this, findings confirm the overall assumption that OEMs tend to have higher component than architectural knowledge. Reasoned by architectural and technical complexity, there is no evidence found that component and architectural knowledge could be assigned clearly to black- and grey-box development in relation to the product architecture. Consequently, on basis of the findings the mirroring hypothesis is unambiguously rejected and therewith provides further evidence that contributes to the discussion of academics about the mirroring hypothesis. Moreover, the findings suggest a minor role of product architecture as predictor of firm-integration, which does not only reject, but also contradicts the mirroring hypothesis.

To date, research has primarily focused on investigating the effects of product architecture, firm integration and knowledge on one component, such as an A/C system and aircraft turbine. This research in turn provides a unique approach by applying a complete product architecture of a complex, technical system. The tractor as vehicle is in terms of its product architecture similar to automobiles, trucks or other motorised vehicles. Therefore, the DSM and subsequent statistical findings are to such an extent generalizable as those can be applied to all kinds of motorised vehicles. Combined qualitative and quantitative analyses allow to gain insights by a) empirical results, and b) take a case wise and explorative perspective.

The DSM has shown to serve as a useful and suitable tool for this research as this depicts clearly the entire incoming and outgoing component interactions as well as their respective component coupling strength. On this way component systems and interactions within and across system boundaries are well recognisable. By taking the complete product of the tractor into consideration, one becomes aware of the complexity and interconnectivity of a technically advanced product. Since complexity of technologies applies to most the existing products, especially technological advanced products such as vehicles and electronic gadgets, this study underlines even more that the simplistic and binary approach of the mirroring hypothesis is obsolete. Grey-box development and knowledge about the components and the constituent product architecture is key to product performance and product consistency. Black-box development requires high component and architectural knowledge as well as distinctively specified and defined components by the supplier, or a component that is fully modular. This is difficult to achieve for a firm, and furthermore, the complexity of a complete product and the numerous component coupling indicate that this is rarely the case in regard to components of component level one and two. Parts of lower component levels, which for instance include bearings, component specific bolts nuts or similar are more likely to be designed independently by a supplier.

12.5. Managerial Implications

Research shows that component parts of a tractor, at least related to the first and second component level, should be developed and sourced carefully and in collaboration with the supplier, reasoned on the significance of grey-box development. It needs to be taken into consideration that none of the components at component level one and two are developed in a black-box approach exclusively, even if high industry design standards of the component architecture were present. Constant involvement of the supplier firms in development processes and the attainment of long-term relationships is advisable for component development at level one and two. It can be assumed that it is beneficial if the suppliers know the product architecture to such an extent that design and development of components perfectly fit in the complete product architecture, without costly re-engineering.

Furthermore, it needs to be taken into account that each component assembly differs even within the same component group. Suppliers provide different levels of modularity for a similar component. Consequently a generalised conclusion and approach how to develop and source which type of component under various conditions is difficult to develop, rather firms should consider unique solutions depending on multiple factors (component architecture, supplier's and own capabilities, buyer and supplier knowledge about the component in question and the final product, pace of component's pace of technology, etc.). Thereby, the DSM is a useful tool to identify critical interdependencies and can be also applied to manage the activities and buyer-supplier integration per component by employing an activity-based DSM.

12.6. Research Limitations and Suggestion for Further Research

Although clearly rejecting the mirroring hypothesis and stressing the importance of knowledge and buyer-supplier integration, the research suffers from a number of limitations. The main research limitation is the limited perspective of the suppliers only. An integration of the buyer's perspective could provide more clarity on buyer's reasons for developing in-house or driving from external sources, and could offer explanations to the question in which way the product architecture and the buyer's degree of knowledge are drivers of development and sourcing decisions.

The study is furthermore conducted at one point in time only, hence implying a 'snapshot' of one moment. A longitudinal study in turn facilitates to investigate how the level of buyer-supplier integration develops in relation to the respective component and overall product architecture, and the respective level of component and architectural knowledge. In addition to this, this research is limited to one company in the agricultural equipment industry and refers to one single product. A more generic picture requires a multiple cross-industry study in order to compare various product architectures in different markets/industries with multiple actors.

Also, the selection of the control variables leads to a rejection of the hypothesis, although the relevant independent variables show significant correlations with the dependent variables. Thus suggests a re-elaboration on the control variables.

Still, it is not clear how and in which way do these multiple variables interact with and influence each other. While this research provides insights of the critical effect of knowledge in terms of component and architectural knowledge, further aspects are not investigated due to the scope of the research. Results indicate high contingency upon multiple factors, of which knowledge is critical, but likely one among many. Further and in-depth research is required to shed light on which drivers and forces of vertical integration, firm relationships, level of component and architectural, product architecture. For instance, various industry settings and firm specifications could be therefore investigated that are likely to influence the product architecture in integrating external sources of technologies and innovations. Further, likely drivers could be the pace of technological change, strategic importance of the component in question, the industry structure, and the effect of design rules and industry standards. In this regard it would be interesting to know what are the starting points of these interdependencies; is it the product and its architecture, the knowledge and capabilities a firm has, or the availability of technology on the market or in the network? And also, in which way do the individual drivers influence firm and product performance?

The survey answers by the suppliers do not show clear distinctions between black- and grey-box development, and component – and architectural knowledge. As these were the core variables, this might have influenced the statistical outcomes. Since the suppliers can be considered as critical suppliers of ABC, survey answers could be biased to favour ABC. Despite the facts that grey-box development is the predominant development approach, and that supplier's component knowledge prevails over architectural knowledge, the research lacks to detect clear rules and patterns of the relationship. As the data is based on two different perspectives - the DSM data is based on ABC's engineers, while the survey data is based on ABC's suppliers - this could cause non-consistent outcomes, which do not lead to the desired findings. In order to align product architecture data (DSM) and firm integration data, a second DSM, namely an activity-based DSM that corresponds the product architecture DSM, could directly show how and to what degree the firm integration related to each component and sub-component. An application of both DSMs would therefore enable a straightforward comparison of component coupling and degree of buyer-supplier integration

Finally, this research focused on an additional predictor (knowledge) of buyer-supplier integration, but a moderation effect of knowledge and/or other variables could also be taken into consideration. The significant correlation between knowledge and buyer-supplier integration gives moreover reason to test curvilinear effects by applying quadratic terms of the independent variable(s) (Dawson, 2014).

Concluding it can be stated that further, in depth research is needed to investigate the interdependencies, drivers and forces of vertical integration, firm relationship, level of component and architectural knowledge and product architecture.

13. Bibliography

Abernathy, W. J., & Utterback, J. M. (1978). Patterns of Industrial Innovation. *Technology Review*, *80*(7), 40–47.

Ambrosini, V., & Bowman, C. (2001). Tacit Knowledge: Some Suggestions for Operationalization. *Journal of Management Studies*, *38*(6), 811–829. doi:10.1111/1467-6486.00260

Amrit, C., & van Hillegersberg, J. (2008). Detecting Coordination Problems in Collaborative Software Development Environments. *Information Systems Management*, *25*(1), 57–70. doi:10.1080/10580530701777156

Anderson, P., & Tushman, M. L. (1990). Technological Discontinuities and Dominant Designs : A Cyclical Model of Technological Change. *Administrative Science Quarterly*, *35*(4), 604–633. doi:10.2307/2393511

Araujo, L., Dubois, A., & Gadde, L.-E. (2003). The multiple boundaries of the firm. *Journal of Management Studies*, *40*(5), 1255–1277. doi:10.1111/1467-6486.00379

Austin, S., Baldwin, A., Li, B., & Waskett, P. (2000). Analytical design planning technique (ADePT): a dependency structure matrix tool to schedule the building design process. *Construction Management and Economics*, *18*(2), 173–182. doi:10.1080/014461900370807

Babbie, E. R. (2010). *The practice of social research* (12th ed.). Belmont, CA: Wadsworth.

Baldwin, C. Y. (2008). Where do transactions come from? Modularity, transactions, and the boundaries of firms. *Industrial and Corporate Change*, *17*(1), 155–195. doi:10.1093/icc/dtm036

Baldwin, C. Y., & Clark, K. B. (1994). *Modularity-in-design: An analysis on the theory of real options*.

Baldwin, C. Y., & Clark, K. B. (2002). *The option value of modularity in design*. *Harvard Business School* (Vol. 1). doi:10.1.1.198.8143

Baxter, P., & Jack, S. (2008). Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers Qualitative Case Study Methodology : Study Design and Implementation, *13*(4), 544–559.

Becker, M. C., & Zirpoli, F. (2011). Beyond product architecture : Division of labour and competence accumulation in complex product development. *Università Ca'Foscari Venecia*, *3*(May).

Browning, T. R. R. (2001). Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *IEEE Transactions on Engineering Management*, *48*(3), 292–306. doi:10.1109/17.946528

Brusoni, S., & Prencipe, A. (2001). Unpacking the black box of modularity: thechnologies, products and organization. *Industrial and Corporate Change*, *10*(1), 179–205. doi:10.1093/icc/10.1.179

Brusoni, S., & Prencipe, A. (2006). Making design rules: A multidomain perspective. *Organization Science*, *17*(2), 179–189. doi:DOI 10.1287/orsc.1060.0180

Brusoni, S., Prencipe, A., & Pavitt, K. (2001). Knowledge specialization, organizational coupling, and the boundaries of the firm: why do firms know more than they make? *Administrative Science Quarterly*, *46*(4), 597–621. doi:10.2307/3094825

Cabigiosu, A., & Camuffo, A. (2012). Beyond the "Mirroring" Hypothesis: Product Modularity and Interorganizational Relations in the Air Conditioning Industry. *Organization Science*, *23*(3), 686–703. doi:10.1287/orsc.1110.0655

Cabigiosu, A., Zirpoli, F., & Camuffo, A. (2013). Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry. *Research Policy*, *42*(3), 662–675. doi:10.1016/j.respol.2012.09.002

Cohen, W. M., & Levinthal, D. A. . (1990). Absorptive Capacity : A New Perspective on and Innovation Learning. *Administrative Science Quarterly*, *35*(1), 128–152.

Colfer, L., & Baldwin, C. Y. (2010). *The Mirroring Hypothesis : Theory , Evidence and Exceptions Lyra Colfer The Mirroring Hypothesis : Theory , Evidence and Exceptions*. *Harvard Business School* (Vol. No. 10–058). Retrieved from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1539592

Creswell, J. W., Hanson, W. E., Clark Plano, V. L., & Morales, A. (2007). Qualitative Research Designs: Selection and Implementation. *The Counseling Psychologist*, *35*(2), 236–264. doi:10.1177/0011000006287390

Crouch, M., & McKenzie, H. (2006). The logic of small samples in interview-based qualitative research. *Social Science Information*, *45*(4), 483–499.

doi:10.1177/0539018406069584

Danilovic, M., & Browning, T. R. (2007). Managing complex product development projects with design structure matrices and domain mapping matrices. *International Journal of Project Management*, *25*(3), 300–314. doi:10.1016/j.ijproman.2006.11.003

Dawson, J. F. (2014). Moderation in managament research: What, why, when and how. *Journal of Business and Psychology*, *29*, 1–19.

Dawson, J. F., & Richter, A. W. (2006). Probing three-way interactions in moderated multiple regression: development and application of a slope difference test. *The Journal of Applied Psychology*, *91*(4), 917–26. doi:10.1037/0021-9010.91.4.917

Eppinger, S. D., & Browning, T. R. R. (2012). *Design Structure Matrix Methods and Applications* (1st ed.). Cambridge, Massachusetts: The MIT Press.

Eppinger, S. D., Whitney, D. E., Smith, R. P., & Gebala, D. A. (1994). A model-based method for organizing tasks in product development. *Research in Engineering Design*, *6*(1), 1–13. doi:10.1007/BF01588087

Fine, C. H., & Whitney, D. E. (1996). *Is the make-buy decision process a core competence? MIT Center for Technology, Policy, and Industrial Development*. doi:10.1017/CBO9781107415324.004

Fixson, S. K. (2005). Product architecture assessment: A tool to link product, process, and supply chain design decisions. *Journal of Operations Management*, *23*(3-4), 345–369. doi:10.1016/j.jom.2004.08.006

Fixson, S. K. (2007). *What exactly is Product Modularity? The answer depends on who you ask. MIT Sloan School of Management*.

Fixson, S. K., Ro, Y., & Liker, J. K. (2005). Modularisation and outsourcing: who drives whom? A study of generational sequences in the US automotive cockpit industry. *International Journal of Automotive Technology and Management*, *5*(2), 166. doi:10.1504/IJATM.2005.007181

Furlan, A., Cabigiosu, A., & Camuffo, A. (2014). When the Mirror gets Misted Up: Modularity and Technological Change. *Strategic Management Journal*, *35*, 789–807. doi:10.1002/smj

Gable, G. G. (1994). Intregrating Case Study and Survey Research Methods: an Example in Information Systems. *European Journal of Information Systems*, *3*(2), 112–126.

Gershenson, J. K., Prasad, G. J., & Zhang, Y. (2003). Product modularity: Definitions and benefits. *Journal of Engineering Design*, *14*(3), 295–313. doi:10.1080/0954482031000091068

Gokpinar, B., Hopp, W., & Iravani, S. (2010). The Impact of Misalignment of Organizational Structure and Product Architecture on Quality in Complex Product Development. *Management Science*, *56*(3), 464–484. doi:10.1287/mnsc.1090.1117

Grant, R. M. (1996). Toward a Knowledge-Based Theory of the Firm. *Strategic Management Journal*, *17*(Winter Special Issue), 109–122. doi:Article

Guba, E. G. (1981). Criteria for assessing the trustworthiness of naturalistic inquiries. *Educational Communication & Technology*, *29*(2), 75–91. doi:10.1007/BF02766777

Henderson, R., & Clark, K. (1990). Architectural innovation: the reconfiguration of existing product technologies and the failure of existing firms. *Administrative Science Quarterly*, *35*(1), 9–30.

Hoetker, G. (2006). Do modular products lead to modular organizations? *Strategic Management Journal*, *27*(6), 501–518. doi:10.1002/smj.528

Hofman, E., Halman, J. I. M., & Looy, B. van. (2016). Do design rules facilitate or complicate architectural innovation in innovation alliance networks? *Research Policy*, *45*(7), 1–12. doi:10.1016/j.respol.2016.04.001

Hsuan, J. (1999). Impacts of supplier–buyer relationships on modularization in new product development. *European Journal of Purchasing & Supply Management*, *5*(3-4), 197–209. doi:10.1016/S0969-7012(99)00026-X

Jaccard, J., Wan, C. K., & Turrisi, R. (2009). The Detection and Interpretation of Interaction Effects Between Continuous Variables in Multiple Regression. *Multivariate Behavioral Research*, *25*(4), 467–478. doi:10.1037/0033-2909.85.4.858

Jacobides, M. G., & Winter, S. G. (2005). The Co-Evolution of Capabilities and Transaction Costs : Explaining the Institutional Structure of Production. *Strategic Management Journal*, *26*(5), 395–413.

Kalaignanam, K., Kushwaha, T., & Nair, A. (2015). Buyer-Supplier Network Structure and Product Architecture. *2015 Academy of Management Annual Meeting*.

King, A. W., & Zeithaml, C. P. (2003). Measuring organizational knowledge: A conceptual and methodological framework. *Strategic Management Journal*, *24*(8), 763–772. doi:10.1002/smj.333

Kotha, S. (1995). Mass customization: Implementing the emerging paradigm for competitive advantage. *Strategic Management Journal*, *16*(Special Issue), 21–42. doi:10.1002/smj.4250160916

Koufteros, X., Vonderembse, M., & Jayaram, J. (2005). Internal and External Integration for Product Development : The Contingency Effects of Uncertainty , Equivocality ,. *Decision Sciences*, *36*(1), 97–134.

Krefting, L. (1991). Rigor in Qualitative Reseach: The Assessment of Trustworthiness. *The American Journal of Occupational Therapy*, *45*(3), 214–222.

Langlois, R. N. (2002). Modularity in technology and organization. *Journal of Economic Behavior and Organization*, *49*(1), 19–37. doi:10.1016/S0167-2681(02)00056-2

Lau, A. K. W., Yam, R. C. M., & Tang, E. P. Y. (2010). Supply chain integration and product modularity. *International Journal of Operations & Production Management*, *30*(1), 20–56.

MacCormack, A., Baldwin, C., & Rusnak, J. (2012). Exploring the duality between product and organizational architectures: A test of the “mirroring” hypothesis. *Research Policy*, *41*(8), 1309–1324. doi:10.1016/j.respol.2012.04.011

Maheswari, J. U., Varghese, K., & Sridharan, T. (2006). Application of Dependency Structure Matrix for Activity Sequencing in Concurrent Engineering Projects. *Journal of Construction Engineering and Management*, *132*(5), 482–490. doi:10.1061/(ASCE)0733-9364(2006)132:5(482)

Mays, N., & Pope, C. (1995). Rigour and qualitative research. *BMJ*, *311*(August), 376–380. doi:10.1117/12.813848

Mikkola, J. H. (2003). Modularity, component outsourcing, and inter-firm learning. *R&D Management*, *33*(4), 439–454. doi:10.1111/1467-9310.00309

Newcomb, P. J., Bras, B., & Rosen, D. W. (1996). Implications of modularity on product design for the life cycle. In *Proceedings of the 1996 ASME Design Engineering Technical Conference and Computer in Engineering Conference* (pp. 1–12).

doi:10.1115/1.2829177

Patel, P. C., & Jayaram, J. (2014). The antecedents and consequences of product variety in new ventures: An empirical study. *Journal of Operations Management*, *32*(1-2), 34–50. doi:10.1016/j.jom.2013.07.002

Piller, F. T. (2005). Mass Customization - Reflections on the State of the Concept. *The International Journal of Flexible Manufacturing Systems*, *16*, 313–334.

Pimmler, T. U., & Eppinger, S. D. (1994). Integration analysis of product decompositions. In *Proceedings of the ASME Design Theory and Methodology Conference* (Vol. DE-Vol 68, pp. 343–351).

Puranam, P., Singh, H., & Chaudhuri, S. (2009). Integrating Acquired Capabilities: When Structural Integration Is (Un)necessary. *Organization Science*, *20*(2), 313–328. doi:10.1287/orsc.1090.0422

Ro, Y. K., Liker, J. K., & Fixson, S. K. (2007). Modularity as a Strategy for Supply Chain Coordination : The Case of U . S . Auto. *IEEE Transactions on Engineering Management*, *54*(1), 172–189.

Salvador, F., Forza, C., & Rungtusanatham, M. (2002). Modularity, product variety, production volume, and component sourcing: Theorizing beyond generic prescriptions. *Journal of Operations Management*, *20*(5), 549–575. doi:10.1016/S0272-6963(02)00027-X

Sanchez, R. (1995). Strategic Flexibilty in Product Competition. *Strategic Management Journal*, *16*(S1), 135–159. doi:10.1002/smj.4250160921

Sanchez, R. (1999). Modular Architectures in the Marketing Process. *The Journal of Marketing*, *63*(Special Issue), 92–111. doi:10.2307/1252104

Sanchez, R., & Mahoney, J. (2012). Modularity and Economic Organization: Concepts, Theory, Observations, and Predictions. *... Economic and Organization Theory*.

Sanchez, R., & Mahoney, J. T. (1996). Modularity, flexibility, and knowledge management in product and organization design. *Strategic Management Journal*, *17*(S2), 63–76. doi:10.1002/smj.4250171107

Sosa, M. E., Eppinger, S. D., & Rowles, C. M. (2003). Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions. *Journal of Mechanical*

Design, *125*(2), 240–252. doi:10.1115/1.1564074

Sosa, M. E., Eppinger, S. D., & Rowles, C. M. (2004). The Misalignment of Product Architecture and Organizational Structure in Complex Product Development. *Management Science*, *50*(12), 1674–1689. doi:10.1287/mnsc.1040.0289

Sosa, M. E., Eppinger, S. D., & Rowles, C. M. (2007). A Network Approach to Define Modularity of Components in Complex Products. *Journal of Mechanical Design*, *129*(11), 1118–1129. doi:10.1115/1.2771182

Sosa, M. E., Gargiulo, M., & Rowles, C. M. (2007). *Component Connectivity, Team Network Structure and the Attention to Technical Interfaces in Complex Product Development*. *ISEAD The Business School for the World* (Vol. 68). doi:10.1287/opre.1080.0628

Takeishi, A. (2002). Knowledge in the Interfirm Partitioning Division of Labor : The Case of Automotive Product Development. *Organizational Science*, *13*(3), 321–338. doi:10.1287/orsc.13.3.321.2779

Teece, D. J. (1977). Technology Transfer By Multinational Firms: the Resource Cost of Transferring Technological Know-How. *Economic Journal*, *87*(346), 242–261. doi:10.2307/2232084

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy*, *24*, 419–440.

von Hippel, E. (1990). Task Partitioning: an Innovation Process Variable. *Research Policy*, *19*, 407–418.

Williamson, O. E. (1985). *The Economic Institutions of Capitalism*. New York: The Free Press.

Williamson, O. E. (1998). Transaction Cost Economics: How It Works; Where It is Headed. *De Economist*, *146*(1), 23–58. doi:10.1023/a:1003263908567

Yassine, A. A. (2004). An Introduction to Modeling and Analyzing Complex Product Development Processes Using the Design Structure Matrix (DSM) Method, 1–17.

Yassine, A. A. (2007). Investigating product development process reliability and robustness using simulation. *Journal of Engineering Design*, *18*(6), 545–561. doi:10.1080/09544820601011690

Zahra, S. A., & George, G. (2002). Absorptive Capacity: a Review, Reconceptualization, and Extension. *Academy of Management Review*, *27*(2), 185–203.

Zhang, Y. (2000). Using the Internet for survey research: A case study. *Journal of the American Society for Information Science*, *51*(1), 57–68. doi:10.1002/(SICI)1097-4571(2000)51:13.0.CO;2-W

Zirpoli, F., & Becker, M. C. (2011). The limits of design and engineering outsourcing: Performance integration and the unfulfilled promises of modularity. *R&D Management*, *41*(1), 21–43. doi:10.1111/j.1467-9310.2010.00629.x

Zirpoli, F., & Camuffo, A. (2009). Product Architecture, Inter-Firm Vertical Coordination and Knowledge Partitioning in the Auto Industry. *European Management Review*, *6*(4), 250–264. doi:10.1057/emr.2009.25