Characteristics of change-able systems across value chains

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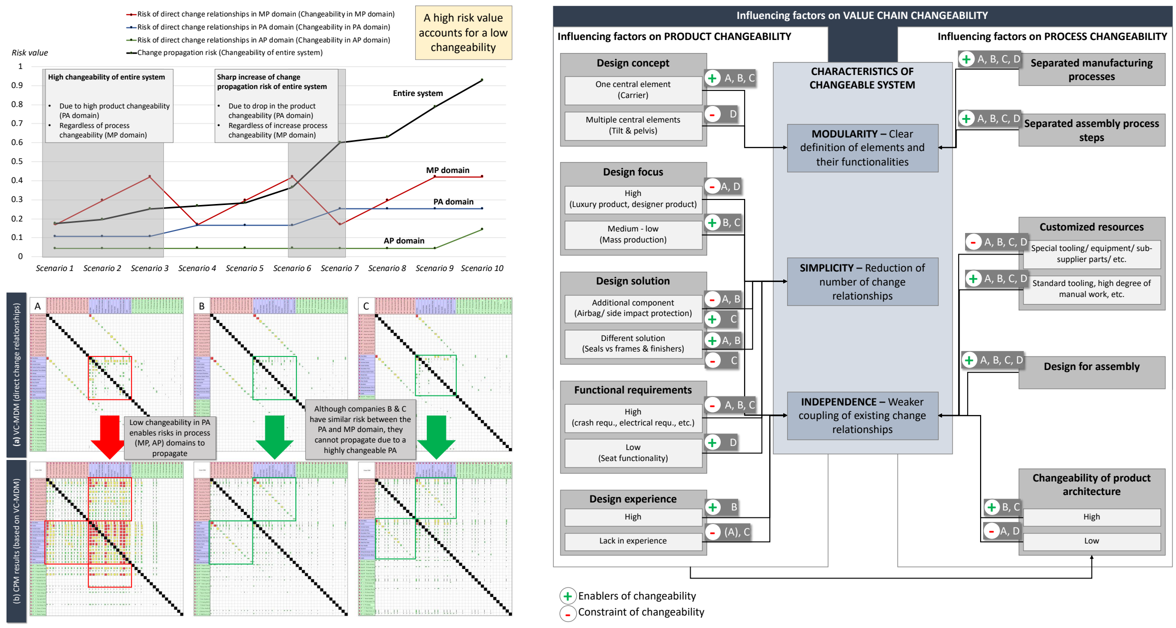

Highlights

- Characterisation of change-able systems across value chains (VC)
- A VC-approach to engineering change assessment that considers product and process dependencies
- A framework that prioritizes changeability concepts to increase the changeability of the entire VC
- Analysis of four case studies: three automotive, one furniture manufacturing
- Product changeability builds the core of a changeable VC (finding 1)
- Factors that influence the changeability in product and processes (finding 2)

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Characteristics of change-able systems across value chains

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Engineering changes (ECs) are inevitable for businesses due to increasing innovation, shorter lifecycles, technology and process improvements and cost reduction initiatives. The ECs could propagate and cause further changes due to existing system dependencies, which can be challenging. Hence, *change management (CM)* is a relevant discipline, which aims to reduce the impact of changes. *EC assessment* methods form the basis of CM that support in assessing system dependencies and the impact of changes. However, there is limited understanding of which factors influence the change-ability across value chains (VCs). This research adopted a *VC approach* to EC assessment. Dependencies in products and processes were captured, followed by the risk (i.e. likelihood x impact) assessment of ECs using *change prediction method (CPM)*. Four case studies were conducted from two industries (automotive, furniture) to identify design (product) and manufacturing (process) elements with high risk to be affected by ECs. Based on the case results, characteristics were identified that influence change-ability across VC. This contributed to the CM domain while businesses could also use the results to assess ECs across VC, and improve the design of products and processes by increasing their changeability across VC e.g. by proactive decoupling or reactive handling of system dependencies.

Keywords: Change-ability; Value chain; Influencing factors; Engineering Change Management; Reconfigure; Automotive; System Dependencies; Design Structure Matrix, Risk Management, Industry 4.0

1. Introduction

It becomes a competitive advantage for manufacturers to control and manage complexities due to the interdependency, increasing volatility, business dynamics, and multidisciplinary nature of products and processes (ElMaraghy et al., 2012) (Masood et al., 2013)(Wiendahl et al., 2007)(Aguila and ElMaraghy 2018). Dependencies between system elements are the key drivers for these complexities (SG, 2004). Instances of system dependencies are the dependencies between product components and process types or the dependencies between internal departments and external partners, and dependencies between customer demand and process lead-times (ElMaraghy et al., 2012)(Masood et al., 2017a).

When changing a product *(EC),* these system dependencies could be particularly difficult due to possibility of change propagation along the existing system dependencies which may cause further changes throughout the system (Terwiesch and Loch, 1999). Consequently, the *CM* literature deals with assessing the impact of *ECs* so that system dependencies can be reduced and, thus, the changeability of the system can be increased (Hamraz et al., 2013a).

Apart from the CM domain, two further literature domains exist where the management of system dependencies plays an important role (*Table 1*).

Table 1

Big picture of system dependencies

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In new product development (NPD), it is challenging to ensure compatibility between various project requirements (Fine, 1998)(Ernst, 2002), e.g. dependent requirements could exist between product specifications and the manufacturing process type, or between the manufacturing lead times, the transportation processes, and the inventory management (Ellram et al., 2007). Changing market environments nowadays drive product lines to dynamically adapt accordingly (Chen et al., 2009), while responsiveness is an underlying idea of changeability (Wiendahl et al., 2007)(Váncza et al., 2011). Thus, *(three dimensional) concurrent engineering* (*(3D)CE*) addresses this challenge by simultaneously developing the product, its processes, and its supply chain in order to ensure the best trade-off between the various project requirements (Fine et al., 2005)(Ilhami et al., 2018).

Wu et al. (2014) combined product lifecycle management (PLM) and enterprise resource planning perspectives (Rashid et al. 2018) to form an engineering change management framework based on configuration management. However, Singh et al. (2020) highlighted that PLM concept has not been properly institutionalised in manufacturing organisations.

Vernadat et al. (2018) highlighted recent advances and new perspectives of information systems and knowledge management in industrial engineering, which include three major thrusts in production research. First thrust is on Industry 4.0 technologies for the factories of the future including Small and Medium Enterprises (Masood and Sonntag 2020), which includes technologies like augmented reality (Egger and Masood 2020)(Masood and Egger 2019)(Masood and Egger 2020), immersive and collaborative artificial-reality in design of human-robot workspaces (Malik et al 2020a)(Malik et al 2020b)(Malik et al 2020c). Second thrust is on creating S^3 enterprises based on sensing, smart and sustainability capabilities while third thrust is on cloud manufacturing which is linked to networked organisations (Rashid et al. 2018))(Vernadat et al. 2018). Though most of these concepts are focus of many recent studies, it is important to first identify, analyse and discuss the core concepts that characterise change-able systems across value chains.

In operations management, systems could face various risks and disruptions. These could cause further risks and disruptions due to their dependencies (*ripple effect*). For instance, a lack in process control and human errors could lead to deviations in supplier quality, which could lead to poor product quality and delayed deliveries (Quang and Hara, 2018)(Qazi et al., 2018). Thus, within *supply chain disruption management* (*SCDM*), it is aimed to build a resilient manufacturing SC to prevent the negative impacts of disruptions on the SC performance (Dolgui et al., 2018)(Ivanov et al., 2014)(Masood et al., 2017a); some may be caused by disasters (Masood et al., 2017b).

Risk assessment is widely used in the safety science, where risk is typically defined as the product of likelihood and impact. There may be two extreme situations: (i) high likelihood but low impact, and (ii) low likelihood but high impact. It's important to discuss how to compare their risks. Typically both cases are treated equally because prioritisation is done based on risk number (i.e. likelihood x impact). Therefore, with this view, either of case (i) or case (ii) would be prioritised as far as their risk number is higher. However, a counter argument would be that a case with higher likelihood but lower impact may be prioritised over higher impact but lower likelihood as there are more chances of that happening in practice.

An extensive literature review has shown that researchers mostly focus on dependencies within a product, and that dependencies with other domains, e.g. manufacturing processes and the supply chain, are not sufficiently addressed. Thus, this research aims to investigate *the influencing factors that contribute to change-ability across VC*.

This article addresses this research aim in six sections: First, the literature on CM – with a focus on change-ability, its assessment and influencing factors – is reviewed and the research question is introduced (*Section 2*). Second, the methodology is presented to address this research question (*Section 3*). Third, the basis of the change assessment method to understand change-ability across VC is developed (*Section 4*). Then, this assessment method is applied to four selected cases (*Section 5*). The results of the cases are analysed to validate the method and to summarize learnings from the cases in terms of influencing factors contributing to change-ability across VCs (*Section 6*). Finally, this paper is concluded with an overview of contributions to knowledge, limitations and proposed future work (*Section 7*).

2. Change-able systems across value chains

This section reviews the literature on change propagation, change assessment methods (*quantification of change impacts*) and changeability concepts across VCs (*mitigation of change impacts*). Lastly, the identified literature gap is presented, and the derived research question is introduced.

2.1 Challenges and characteristics that influence change propagation

In *change management* (*CM*), throughout the entire product lifecycle focus is on the task of modifying a released system (Eisa et al., 2018)(Karthik and Reddy, 2016). These systems could be products (*engineering changes* (*EC*)) (Ullah et al., 2016), or factory systems (*manufacturing changes* (*MC*)) (Koch et al., 2016). Changes in these systems could be either triggered by problems (*emergent changes*) or by the introduction of new product and process specifications (*initiated changes*) (C. Eckert et al., 2004).

It is challenging that changes could propagate along the existing system dependencies and cause further changes throughout the system (Terwiesch and Loch, 1999)(Schuh et al., 2017). Jarrett et al. (2011) summarized three characteristics that influence change propagation: the number, the specification and the complexity of system dependencies.

Therefore, it is aimed within CM, to reduce the change impact by proactively reducing or reactively handling system dependencies (Fricke et al., 2000)(Hamraz et al., 2013a). This objective is operationalised with change assessment methods that quantify the change impact and with changeability concepts that mitigate the change impact across VCs (Hamraz et al., 2013b)(Huang and Mak, 1999). Both are reviewed in more detail in the following sections.

2.2 Why is it important to assess the change propagation?

Assessment of change propagation helps in evaluating the dependencies within a system and quantifying the impact of changes (Masmoudi et al., 2017)(Giffin et al., 2009). This information forms the basis for systematic decision-making in CM, which is crucial to design, engineer and transform manufacturing (Masood and Weston, 2013). The purpose of change assessment methods (C1) can be categorised into *proactive* and *reactive* decision making.

In proactive decision-making, the change impact is assessed to prevent changes in critical areas (Yin et al., 2017)(Giffin et al., 2009)(Lee and Hong, 2015) and to increase the changeability in both the product (Koh et al., 2015)(Schuh et al., 2017) and the processes (Hawer et al., 2017)(Plehn et al., 2016). In reactive decision-making, the change impact is assessed to compare different change options (Koh et al., 2012)(Ullah et al., 2017) and to implement changes more effectively and efficiently (Pasqual and De Weck, 2012)(Kocar and Akgunduz, 2010)(Ou-Yang and Cheng, 2003). Some assessment methods address both proactive and reactive decision-making (Clarkson et al., 2004)(Hamraz and Clarkson, 2015)(Brooks and Mocko, 2011)(Morkos and Summers, 2010).

2.3 How is the change propagation assessed? (C2)

Based on their assessment scope, three types of methods are prominent in literature: (i) *EC assessment methods*: Assessment of dependencies within the product domain, (ii) *Multi-domain EC assessment methods*: Assessment of dependencies within the product domain in combination with other domains, and (iii) *MC assessment methods*: Assessment of dependencies within the manufacturing domain. The assessment scope consists of the elements between which the impact of changes is assessed. In the reviewed assessment methods, elements are considered from four domains: product, manufacturing, supply chain and others.

2.3.1 EC Assessment Methods

The dependencies between product components are assessed by the methods with the lowest granularity (Clarkson et al., 2004)(Koh et al., 2013)(Keller et al., 2005)(Ullah et al., 2017)(Ou-Yang and Cheng, 2003)(Lee and Hong, 2015)(Ullah et al., 2018)(Koh, 2017). Methods with a higher granularity decompose the product into different layers (structure, behaviour, function) (Hamraz and Clarkson, 2015), into product parameters (Masmoudi et al., 2017)(Yin et al., 2017) and into degrees of freedom (Schuh et al., 2017). Consequently, the dependencies within a product are described from different levels of detail. It must be noted that the required level of detail could differ depending on the required accuracy and accepted complexity of the assessment methods (Koh, 2017).

2.3.2 Multi-Domain EC Assessment Methods

The EC assessment methods that also consider the dependencies between the product and other domains are limited. Pasqual and De Weck (2012) and Ahmad et al. (2013) considered the dependencies with the design tasks. Design resilience has also been discussed in the literature in terms of (i) versatility which may be enhanced by introducing active design flexibilities, and (ii) responsiveness which may be enhanced by passive design flexibilities (Alblas and Jayaram 2015).

Some literature indirectly considered the impact on manufacturing processes without specifying and integrating elements of the manufacturing domain in the assessment methods (Reddi and Moon, 2013)(Fei et al., 2011)(Kocar and Akgunduz, 2010)(Brooks and Mocko, 2011). Morkos et al. assess the dependencies with project requirements, such as the requirements on the project schedule, documentation, training, costs and others (Morkos and Summers, 2010)(Morkos et al., 2012)(Hein et al., 2017).

In literature on production research, hybrid modelling approaches have been proposed for assessing the impact of performance in complex make(or engineer)-to-order supply chains (Barbosa and Azevedo 2019). Some researchers assess the impact on capacities of manufacturing processes (Leng et al., 2016)(Meyer et al., 2014)(Li et al., 2017) and of the supply chain network (Wänström and Jonsson, 2006). Yin et al. (2016) consider the topological dependencies with assembly tooling (Yin et al., 2016). Some assessment methods capture the dependencies with process resources and process parameters (Siddharth and Sarkar, 2017)(Hoang et al., 2017)(Do et al., 2008).

Masood et al. (2017a) assessed implications of product architecture changes in conjunction with supply network design during the early stages of product design to increase the resultant resilience of the offsite manufacturing supply network. Moreover, this review shows that only about half of these methods consider dependencies between the product and its processes.

2.3.3 MC Assessment Methods

Some literature is focussed on another type of methods covering only dependencies within a manufacturing system (Plehn et al., 2016)(Gernhardt et al., 2016)(Bauer et al., 2017).

2.4 Modelling Approaches used in Change Assessment Methods (C3)

The most commonly used method to model (direct) dependencies between system elements is design structure matrix (DSM). A variety of approaches exist that predict the impact of changes based on the DSM model. One of the most established is the change propagation method (CPM) that identifies indirect change relationships and determines the risk for change propagation (Clarkson et al., 2004)(Keller et al., 2005)(Koh, 2017)(Schuh et al., 2017)(Masood et al., 2017a). Similarly, a variety of other algorithms exist that identify the risk of indirect change relationships (Ullah et al., 2018)(Li et al., 2017)(Shankar et al., 2017). Delta DSMs identify the change propagation risk by overlaying the initial dependency DSM with higher order DSMs. These are determined based on the analysis of historic change data or a manual specification of potential change propagation paths (Giffin et al., 2009)(Morkos and Summers, 2010)(Hein et al., 2017). Other DSM-based change assessment methods adopt equations (Brooks and Mocko, 2011), nested-pattern analysis (Meyer et al., 2014) and DMM-to-DSM conversions (Koh et al., 2015) to quantify the change impact.

Furthermore, other approaches are found that capture dependencies and assess change impacts. A variety of network models exist (Wynn et al., 2014)(Ahmad et al., 2013), especially Bayesian network models (Mirdamadi et al., 2018)(Lee and Hong, 2015)(Hu and Cardin, 2015). Do et al. (2008) analysed historic change data to determine dependencies and predict future changes. Moreover, changes have also been evaluated in a CAD environment (Malak and Aurich, 2013)(Kocar and Akgunduz, 2010).

Some researchers developed frameworks for a qualitative assessment of change impacts (Wänström and Jonsson, 2006)(Gernhardt et al., 2016)(Bauer et al., 2017). Systematic model-driven approaches to enabling competitive design and change capability in manufacturing enterprises exist (Masood and Weston, 2013; Masood et al., 2013; Masood and Weston, 2012), covering various production management and modelling levels with views of product dynamics, customer order decoupling points, work dynamic, performance metrics, enterprise modelling (static) and simulation modelling. A recent example is related to digital twin based simulations of collaborative robots for reconfiguring existing factories and ramping-up production of medical ventilators in the face of pandemics like COVID-19 while following social distancing rules (Malik et al. 2020a)(Malik et al. 2020b).

2.5 Literature Gap and Its Relevance

The CM domain consists of a variety of research that has recognized the need to control system dependencies and to reduce the impact of changes, especially of ECs. Thus, this domain covers a variety of EC assessment methods that aim to predict change impacts to support proactive and reactive decision-making in CM. However, the review of these EC assessment methods shows that change prediction is mostly limited to the product domain, and that dependencies between the product and other domains are not sufficiently addressed. Hence, **characteristics of change-able systems across value chains are largely unknown.**

It is also evident from the literature review that there is a reported gap that **assessment of ECs lacks in the consideration of other domains, especially of the process domain** (Siddharth and Sarkar, 2017)(Ullah et al., 2017)(Plehn et al., 2016)(Koch et al., 2016)(Hamraz and Clarkson, 2015)(Hamraz et al., 2012)(Koh et al., 2012).

Furthermore, other research areas already address the need to manage the dependencies between the product and processes. For instance, within (3D)CE, it is aimed to trade-off the dependencies between products and processes during the NPD stage (see Section 2.1.1). Moreover, within CM, various tools exist that aim to support the communication of ECs between product designer and process stakeholders, but without assessing the change impact (Tavčar et al., 2018)(Subrahmanian et al., 2015)(Shankar et al., 2012)(Reddi and Moon, 2011)(Wasmer et al., 2011)(Stanev et al., 2008)(Tavčar and Duhovnik, 2005)(Yang et al., 2004).

Therefore, the conclusion can be drawn that **insights from EC assessments are limited to understand the characteristics of change-able systems from a VC perspective, have a high relevance but have not been sufficiently addressed**. In this case, a VC perspective means that the product and its processes are simultaneously considered.

2.6 Research Question and Objectives

To address the identified literature gap, this research aims to improve decision-making in CM by understanding the influencing factors contributing to change-ability across VCs through EC assessment. Thus, the impact of ECs on processes could be identified, and the changeability of the entire VC can be systematically improved. This research addresses the following overarching research question:

RQ*:* *What are the characteristics of change-able systems across the entire VC?*

This research question is broken down into three sub-questions addressing different research objectives:

*(**RQ1**) How can a **VC approach** be created by integrating the **process view** with the **product view**?*

Objective (**RO1**): To identify dependencies within and between the product and process domains.

*(**RQ2**) How can **ECs** be assessed from a **VC perspective**?*

Objective (**RO2**): To create an assessment framework that (i) captures the dependencies between the product and its processes, and (ii) predicts change impacts across these domains.

(RQ3) How can the assessment results be used to improve the ***changeability of the entire VC****?*

Objective (**RO3**): To analyse the results of the assessment framework in supporting proactive and reactive decision-making by reducing the impact of changes across the entire VC (in the product and process domain).

The remainder of this article aims to answer these research questions.

3. Research Methodology

The following section introduces the research methodology that is used to address the above-mentioned research questions (**RQ**). The methodology was selected based upon the literature analysis of EC assessment methods (see Section 2).

Figure 1 summarizes the methodology of this research. The four steps of the CPM form the basis of this research, which will inform the detailed analysis of influencing factors contributing to change-ability across VCs. First, a multi-domain model (MDM) is developed to integrate the product and process view (**RO1&2**). Then, direct change relationships are identified in four cases (**RO2**). Later, the CPM algorithm (based on Clarkson et al. 2004) is used as part of Cambridge Advanced Modeller to determine the change propagation risks and to identify high-risk elements (**RO2&3**). Further analysis is done to discuss the improvement of decision-making with the VC-CPM and to summarize learnings from each case study (**RO3**).

Figure 1

Research methodology based on CPM approach

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4. Model Development

In this section, the MDM model is developed, which integrates a VC perspective (**RO1&2**). In this paper this specific MDM is also referred to as ***VC-MDM***.

This VC-MDM was developed in an exploratory case study with company A (*see Section 5.1*), which focused on an automotive door trim panel. A top-down approach consisting of four steps to develop the VC-MDM model (*Figure 2 (a)*) was adopted, which is described in the following sections.

Figure 2

Basis of the VC-MDM approach

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In this section it is presented how to integrate a product and process view into the VC-MDM (**RO1**). This VC-MDM forms the basis of the VC-CPM to assess ECs from a VC perspective (**RO2**). *Figure 2 (a)* also shows the derived VC-MDM that represent the product and process view of company A's door trim panel.

The findings from the exploratory case are generalized in a framework that supports the development of a VC-MDM (*Figure 2 (b)*): The VC-MDM is specifically developed to assess the architectural dependencies (Step 1) within and between the product architecture (PA), manufacturing process (MP) and assembly process (AP) domains (Step 2). If these prerequisites are applicable, then the elements of the three domains are determined by defining the product components (PA), their associated MPs and their associated AP steps (Step 3). Last criteria are defined to rate the change relationships in each domain (Step 4). Then, the VC-MDM can be used for the VC-CPM.

5. Overview of Case Studies

The derived VC-MDM was applied to three automotive cases to capture the architectural dependencies of the door trim panel in the product and process domains (**CPM-Step 2**). Afterwards, the CPM results were generated to assess ECs from a VC perspective (**CPM-Step 3&4**). Analogues, a fourth case was conducted in the furniture industry with a focus on a designer office chair.

This section summarizes the case study results after introducing the background of the four case companies.

5.1 Company Profiles

Three cases were conducted at the UK-based assembly plants of three international car manufacturers (named as companies A, B and C in this paper). These manufacturers are specialised in different target customer segments.

Company A targets the luxury segment and offers their customers a very high degree of customization, e.g. by offering bespoke colours, bespoke materials and bespoke interior applications. The manufacturing of all components is completely outsourced, except of bespoke leather and wood applications. The car assembly is completely done in-house and has a daily production volume of five cars.

On the other hand, **companies B and C** are specialised in mass production with a production volume of approximately 1000 cars per day. Thus, their customization scope is limited to a predefined selection of variants. However, company C offers their customers a broader and more expensive variant selection than company B, e.g. in the surface materials and application systems of the interior. Both companies outsourced the manufacturing of all components, and even some sub-assemblies while the final assemblies of the cars are done in-house.

The fourth case study was conducted at the UK-based assembly plant of an international furniture manufacturer (**company D**). This manufacturer is specialised in office furniture, equipment and home furnishings. Compared to the whole furniture market, company D addresses the premium customer segment. A key value of company D is its unique and exclusive design, which is fully designed in-house.

Like the automotive companies, the manufacturing of most components is done by suppliers, and the assembly is completely done in-house. The production plant has a daily capacity of producing 400 chairs.

Table 2 summarizes the main characteristics of the four case companies. Furthermore, it provides an overview of the interviewed people.

Table 2

Summary of company profiles and overview of interviewed people

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The VC-CPM was applied to four cases: Based on the derived VC-MDM model (*see Section 4*), direct change relationships were captured in the product and process domains (**CPM-Step 2**). Then, the CPM algorithm was used to generate the risk for change propagation (**CPM-Step 3&4**).

These four cases contribute to the above-mentioned research objectives in two ways: First, the VC approach to EC assessment was validated by showing that dependencies could be captured and assessed in the product and process domains (**RO2**). Second, based on the CPM results, high-risk elements could be identified across both domains that can be used for proactive and reactive decision-making in CM (**RO3**).

In the following section, analyses and discussion are presented based on the results of these case studies.

6. Analysis and Discussion of Results

The VC-CPM results are analysed and discussed in this section.

6.1 Improvement of Decision Basis

In this research, change drivers (aka change multipliers, which are high-risk elements that can drive changes to many other elements) and change absorbers (that have certain redundancy designed into so that to absorb a degree of change) were identified. This builds the basis for decisions to reduce the impact of changes. Then, the CPM results of the VC-CPM are compared with the CPM results of a PA-CPM to investigate whether the basis for decision-making differs in both CPMs. This comparison is based on following criteria:

(**C1**) It is analysed whether the VC-CPM identifies within the PA domain different change drivers and absorbers than the PA-CPM.

(**C2**) It is analysed whether the VC-CPM identifies new high-risk elements from the MP and AP domains.

Figure 3 (a) demonstrates a comparison of both CPMs, which are based on company D's case results. It compares the identified change drivers of the VC-CPM with the ones of the PA-CPM. The analysis of **C1** shows that the VC-CPM provides a new ranked order of the PA-elements. For instance, the pelvis and the tilt have a much higher risk in the VC-CPM than in the PA-CPM. The reason for this is that the VC-CPM captures the high change propagation risks with the MP of the back and the tilts (*see Figure 3 (a)*). The analysis of **C2** shows that new elements from the MP and AP domain, such as the MP and AP of the back, appear within the top change drivers.

Figure 3

Comparison of VC-CPM and PA-CPM results

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Figure 3 (b) summarizes the comparisons for all four cases. First, the results show that on average nearly 50% of the PA elements are ranked differently in the VC-CPM (**C1**). Second, on average over 30% of the identified high-risk elements are from the MP and AP domains (**C2**). Thus, the conclusion can be drawn that the VC-CPM has the potential to improve the decision basis in CM as through the adopted VC approach the impact of ECs on processes is considered.

6.2 Decision-Making Based on the VC-CPM

To support decision-making based on the VC-CPM, a scenario analysis was conducted that investigated the effectiveness (and interaction) of product and process changeability. Ten scenarios were defined that represented a different degree of changeability in the PA, MP and AP domains. These scenarios were set up based on company C's case study results by adapting the risk values of the direct change relationships. A low risk value represents a high degree of changeability (*Figure 4*). For each scenario, the CPM results were generated to investigate the effectiveness of product and process changeability (*Figure 5*).

Figure 5 provides visualisation, and *Figure 6* summarizes the CPM results of the 10 scenarios. The results show that the product changeability is the main factor that determines the changeability of the entire system. Scenarios 1/ 2/ 3 show that regardless of the process changeability the overall risk of change propagation is low as the product has a high changeability (low risk of direct change relationships). On the other hand, scenario 6 and 7 show that the overall risk of change propagation strongly increases when the changeability of the product decreases.

Another observation can be made on the basis of *Figure 5*: Although the MP elements have no direct change relationships, they show a high indirect dependency when the product and process changeability is low (see scenarios 9/ 10). This means that a change in one MP could affect another MP. To prevent this and to mitigate the impact of a coupled PA, highly changeable MPs are required (see scenario 7).

Figure 4

Scenarios with different product (PA) and process (MP, AP) changeability

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Figure 5

CPM results representing the changeability of the entire VC

---Insert Figure 5 Approximately Here---

Figure 6

Product changeability as main driver for changeability of entire VC

---Insert Figure 6 Approximately Here---

The scenario analysis has shown that the product changeability (i) is the main driver for the changeability of the VC, and (ii) is the root cause of indirect change relationships between processes. These findings must be considered when using the VC-CPM for decision-making. A framework (*Figure 7)* is derived that integrates these findings into the VC-CPM so that the most effective changeability concepts can be selected:

(1) Concepts for a changeable PA have *the highest priority* as they form the basis of a changeable system.

(2) However, if a changeable PA could not be achieved, *the second priority* is assigned to changeable processes.

(3) If the system still consists of a coupled PA and specific processes, it is likely that (in-house and outsourced) processes show high indirect dependencies. Thus, *the third priority* is a close collaboration between the suppliers and departments that are responsible for the high-risk MPs and APs.

Figure 7

Framework to create a changeable value chain using the VC-CPM

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6.3 Changeability Characteristics – Comparison of Cases

Different change propagation risks (CPM results) were identified within the four case studies (*Section 5*). The reason for different change propagation risks is that the four companies have different direct change relationships within their ecosystems (PA, MP and AP domains) (*Section 6.2*).

The following section compares the four VC-MDMs (showing the direct change relationships) and highlights factors that influence the direct change relationships, and, thus, the changeability of the whole system. The differences in the direct change relationships are investigated based on the three changeability criteria (Fricke and Schulz, 2005):

- Modularity: Pattern of change relationships
- Simplicity: Number of change relationships
- Independence: Risk value of change relationships

First, a comparison within the automotive industry is made, followed by a cross-industrial comparison with the furniture industry.

6.3.1 Comparison within Automotive Industry

The following section compares, firstly, the direct change relationships within the PA domain, followed by a comparison of the direct dependencies between the product (PA) and process (MP, AP) domains.

Changeability within PA Domain

Overall, the three cases have a similar pattern of change relationships (*modularity*), which shows the most and the strongest change relationships at both the door body and the carrier (*Figure 8 (a)*). The three car manufacturers adopt the same design concept, where the carrier builds the main interface between the exterior (door body) and the interior. This means the purpose of the carrier is to integrate all components of the door trim panel into the door body. This design concept enables a high modularity, which allows to design the door trim panel independently from the rest of the car.

Figure 8

Analysis of results: Design focus

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However, although the three car manufacturers adopt a similar design concept, they face differences in the number (*simplicity*) and strength (*independence*) of their change relationships. The following criteria explain these differences:

- Design focus: In the workshop, company A stated that they expect higher dependencies within their PA than a mass producer, such as company B and C. The reason for this is that company A to offers their customers a highly customized luxury product. This high design focus causes a more complicated product with more and stronger dependencies between their PA elements. For instance, stronger change relationships (*independence*) exist for the carrier as it integrates many bespoke parts, and more change relationships (*simplicity*) exists for the armrest carrier as it is a bespoke part that must be integrated in the environment of the door trim panel (*Figure 8 (b)*).

- Design solutions: Also, the use of different design solutions could cause more and stronger change relationships. For instance, company C uses seals that show stronger change relationships with the door body than the window frames and inner waist rail finishers, which are used by companies A and B. Another example is that companies A and B have further change relationships within their PA as they integrate the airbags/ side impact protections into the door trim panel, which are not integrated by company C (*Figure 8 (c)*).
- Design experience: During the workshops, company C highlighted several times that for some solutions they lack experience, which could cause less standardized component interfaces and, thus, stronger change relationships. Examples are the dependencies between the carrier and the speaker, carrier surface and decorative trims. On the other hand, company B, which seemed to be more experienced, has weaker change relationships in these areas (*Figure 8 (d)*).

Changeability between Product (PA) Domain and Process (MP & AP) Domains

A comparison of the VC-MDMs shows that the three car manufacturers have similar change relationships between the product (PA) and process (MP & AP) domains (*Figure 9* ***Error! Reference source not found.****(a)*).

Overall, the process domains show a high modularity as no direct change relationships (topological dependencies) were identified within the MP domain and within the AP domain. The reason for this is that the product components are produced in separated MPs – even at different suppliers – and assembled in separated AP steps.

Strong change relationships exist between the product components and their associated MPs, whereas the change relationships with the associated APs are low (*simplicity*):

- Customized resources: The MPs adopt a variety of resources (e.g. tooling, equipment, sub-supplier parts) that are customized according to the topological characteristics of the product components. For instance, all companies require a special press tooling for the door body and a special injection moulding tooling for the carrier. On the other hand, the AP adopt standardized tooling, such as screw drivers, and have a high degree of manual work, which results in a low change relationship with the product components.

- Design for assembly: Another reason for the high changeability in the APs is that the door trim panel is designed for assembly, which means that most of the components are easily assembled by clipping or screwing them together.
- Low changeable PA: A highly coupled PA is another driver for high change propagation risks within the process domains. *Figure 9* (b) shows that the strong dependencies between the MPs and PA domain only propagate in the case of company A due to its highly coupled PA. This also corresponds with the results from the above-mentioned scenario analysis (*Section 6.2*).

Figure 9

Changeability between product domain and process domains

(a) Cases A, B, C show similar change relationships between the product (PA) and process (MP & AP) domains; (b) Impact of product changeability on change propagation risk in process domains; highest impact in case of company A

---Insert Figure 9 Approximately Here---------------------------------------

6.3.2 Comparison between Automotive and Furniture Industry

The CPM results show that company D faces overall a high change propagation risk, which differs to the CPM results of the automotive cases. The following section compares the VC-MDMs and highlights the similar and different criteria that influence the changeability (direct change relationships) at company D.

Changeability within Product Architecture Domain

The patterns of change relationships (*modularity*) differ between company D and the car companies. Similar to the carrier of the door trim panel, the tilt forms a central element for most of the components of the chair. However, due to the design concept of the chair, the pelvis forms another central interface for the components of the chair. Thus, the chair has a lower modularity due to the use of multiple core elements (*Figure 10*).

Figure 10

Design concept with multiple core elements used in chair (company D) compared with other cases

--***Insert Figure 10 Approximately Here***--------------------------------------

Furthermore, compared to the automotive cases, company D has less (*simplicity*) but stronger (*independence*) change relationships. This could be explained with the following criteria:

- Functional requirements: Within the door trim panel, several change relationships exist due to functional requirements on the product. For instance, wiring harnesses are required to support the functionalities of the switches, lights and speakers. Other examples are multiple dependencies to the door and carrier due to crash requirements. On the other hand, the chair has less functional requirements which reduces the number of dependencies (*Figure 11 (a)*).
- Design focus: However, the chair has more (*simplicity*) and stronger (*independence*) change relationships due to the high design focus. A striking example is the back that links to the arm assembly, pelvis and spine only due to optical reasons (*Figure 11 (b)*).

Figure 11

Change relationships due to functional requirements and design focus

--***Insert Figure 11 Approximately Here***--------------------------------------

On the other hand, the car manufacturers – especially company B and C – have weaker and less change relationships as they decouple the shape of a component from their interfaces to other components.

Changeability between Product (PA) Domain and Process (MP & AP) Domains

In the process domains, no differences could be identified between both industries. Like the automotive industry, company D deploys special resources in their MPs (especially injection moulding tooling), which causes high change relationships with its associated components. On the other hand, all AP steps – except the one of the back – use standard tooling and a high degree of manual work, which makes the AP steps independent from its associated components.

6.3.3 Theory development - Overview of Characteristics / Influencing Factors on Value Chain Changeability

The CPM results have shown that the four case companies face different change propagation risks in the product and processes. The reason for this are the differences in the direct change relationships that lead to a different degree of changeability.

In the previous sections, the direct change relationships (VC-MDMs) were compared based on the three changeability criteria (modularity, simplicity, independence). *Figure 12* summarizes the identified characteristics / influencing factors and the case specific findings that enable and constraint the product and process changeability. This provides an evidence base to verify and extend the existing theoretical frameworks on change-ability of value chains. The influencing factors on product changeability are further categorised as design concept, design focus, design solutions, functional requirements and design experience. On the other hand, the influencing factors on process changeability are further categorised as separated manufacturing processes, separated assembly processes, customised resources, design for assembly and changeability of product architecture. The enablers of changeability are marked with (+) signs while constraints for changeability are marked as (-) signs. For example, in design concept, one central element (carrier) is an enabler (+) for A, B and C while having multiple central elements (tilt and pelvis) is a constraint (-) for D. The applicable case studies are stated as A, B, C and D.

Figure 12

Characteristics/ influencing factors of VC changeability depending on product and process changeability; case specific examples from company A/B/C/D highlighted

---Insert Figure 12 Approximately Here---------------------------------------

6.4 Summary of Discussion

In *Section 4*, a VC approach was proposed for EC assessment by developing a VC-MDM that integrates a process and a product view (**RO1**). This VC-MDM was applied in four cases to capture dependencies in the product and process domains. Then, the CPM algorithm was applied to assess ECs from a VC perspective (**RO2**) and to identify high-risk elements for further decision-making in CM (**RO3**).

Based on the case results, aspects of how to use the VC-CPM to identify characteristics of change-able systems and improve the changeability of the entire VC were discussed (**RO3**):

- Section 6.1: The comparison with the PA-CPM showed that adopting a VC approach to EC assessment has the potential to improve the decision basis in CM. Compared to a PA-CPM, the VC-CPM identifies different high-risk elements from the PA elements and new high-risk elements from the MP and AP domains.
- Section 6.2: The scenario analysis has shown that the product changeability is the main driver for a changeable VC. Thus, when using the VC-CPM, the impact of different changeability concepts must be considered.
- Section 6.3: Based on the comparison of the case study results, different factors were identified that influenced the changeability of the VC. These must be considered when designing the products and processes.

7. Conclusion

7.1 Contribution to Knowledge

In this research, characteristics of change-able systems across VCs have been identified and highlighted through adopting a VC approach to EC assessment which considered product and process dependencies. The outcome of this research contributes to following areas of the CM literature:

1) Changeability concepts: Based on the analysis of the CPM results, two findings were made about how to improve the changeability of the entire VC.
    a. First, it was identified that the product changeability builds the core of a changeable VC. A framework was developed that prioritizes the different changeability concepts (in product and process) to increase the changeability of the entire VC (*see Section 6.2*).
    b. Second, based on the comparison of the four cases, factors were identified that influence the changeability in product and processes (*see Section 6.3*). Thus, the characteristics of change-able systems across VCs were identified and highlighted.
2) Industry knowledge: The insights, detailed analysis of results and cross-comparison of four case studies covering a broad range of products (from very broad variant selection and bespoke components to unique design), segments (luxury, compact and premium), organisation size (from 1,500 to >100,000 employees) and revenues (from $2Bn to $250Bn) are also considered as contribution to knowledge (*see Sections 5-6*).

7.2 Implication for Industry

The framework for a change-able VC (*see Section 6.2*) and the factors that influence the product and process changeability (*see Section 6.3*) can be used in combination with the VC-CPM to effectively improve the changeability of the VC. Moreover, the VC-CPM can be used by manufacturers to assess ECs from a VC perspective. The applicability has already been verified by applying the VC-CPM to four cases.

However, one point was highlighted throughout the cases that the VC-CPM gives only an indication about the risk of a change. Another factor that must be included in decision-making in CM is the need of a change. Company A gave the example that changes might be due to legal requirements, customer relevant issues, cost improvement or other reasons. Depending on the need of a change, they would accept a different risk of a change. Thus, the VC-CPM must be integrated in a bigger picture of decision making in CM.

7.3 Limitations and Future Work

Throughout the research project, some limitations and potential for future work emerged. In the development of the VC-MDM, an architectural dependency was selected to integrate the product and process views. Dynamic dependencies between both domains were not considered. Thus, an opportunity for future work is to create a VC approach considering the dynamic dependencies. Four cases were conducted to validate the VC-CPM, whereas three of them focused on the automotive door trim panel. Further cases would increase the validity of the method and provide further insights in how to improve the method. A scenario analysis was performed to investigate the impact of product and process changeability on the changeability of the entire VC. In a next step, it is proposed to make a more detailed analysis by investigating specific changeability concepts that determine the product and process changeability.

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Declaration of Interest

None.

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Tables:

Table 1: Big picture of system dependencies

	(3D) Concurrent Engineering	SC Disruption Management	Change Management
Part of…	New product development	Operations management	Lifecycle management
Challenge caused by system dependencies	Ensuring compatibility between various project requirements	Managing ripple effect of disruptions	Managing change propagation
Objective	Optimum trade-off between project requirements	Resilient supply chain	Mitigation of change impact

Table 2: Summary of company profiles and overview of interviewed people

Characteristics	Company A	Company B	Company C	Company D
Product specifications	Very broad variant selection & bespoke components	Medium variant selection	Broad variant selection	Unique design
Product segment	Luxury	Compact	Premium	Premium
Industry	Automotive	Automotive	Automotive	Furniture
Revenue	$250M	>$50Bn	$25Bn	$2Bn
No. of employees	1,500	>100,000	50,000	8,000
Manufacturing of components	Outsourced, except bespoke parts	Outsourced	Outsourced	Mostly outsourced
Car assembly	In-house	In-house; sub-assemblies like door casing are outsourced	In-house; sub-assemblies like door casing are outsourced	In-house
Production volume (cars or chairs/ day)	5	1300	1000	400
Interviewed people (years of experience)	Manger, quality interior (12)/ Quality engineer (11)	Manager, quality interior (14)/ Quality engineer (15)/ Quality engineer (20)	Manager, production vehicle team (30)/ Quality engineer (20)/ Engineer of door assembly line (3)	Manger, chairs assembly (10)/ Manager, screen assembly (4)

Figures:

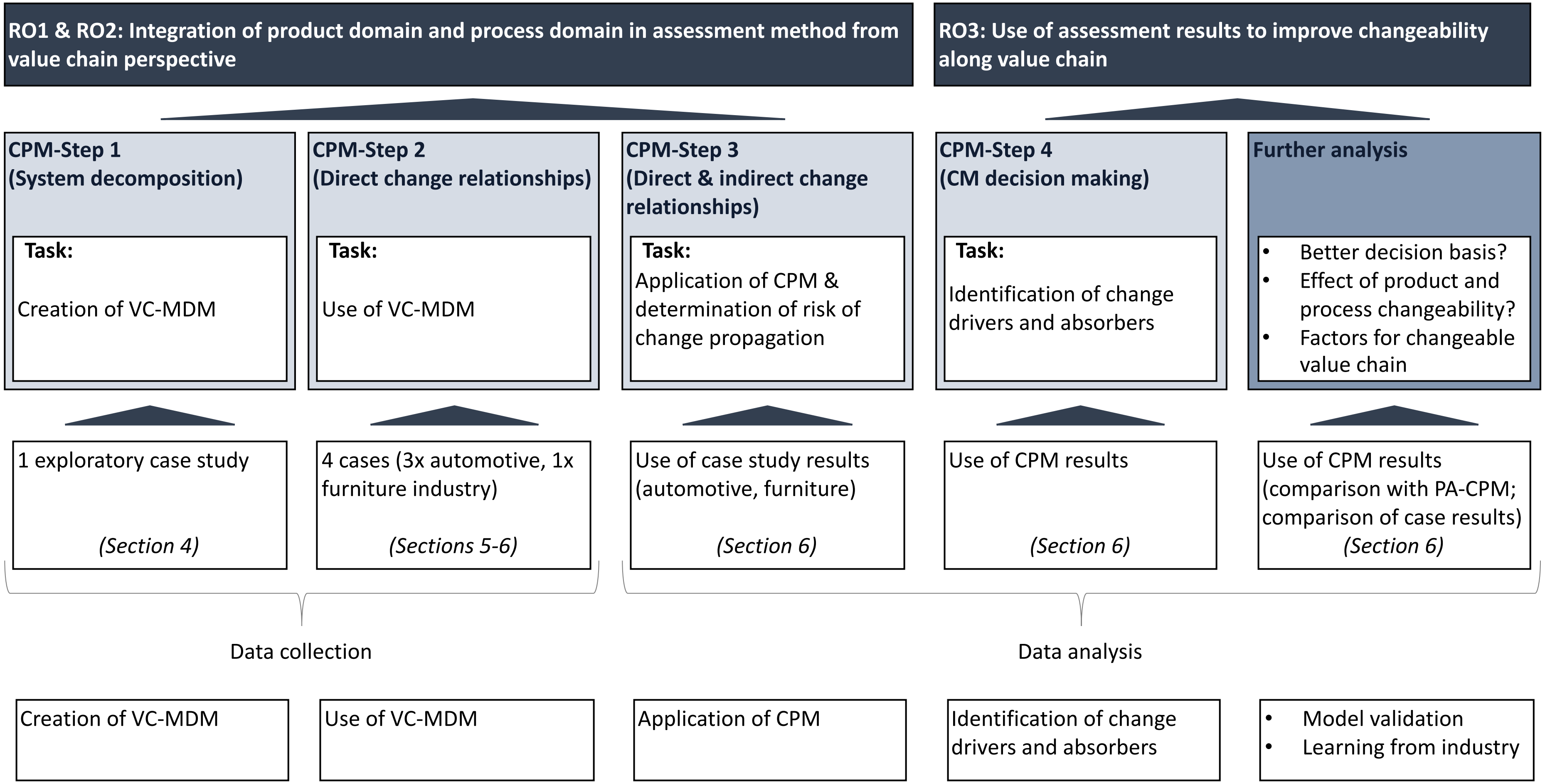
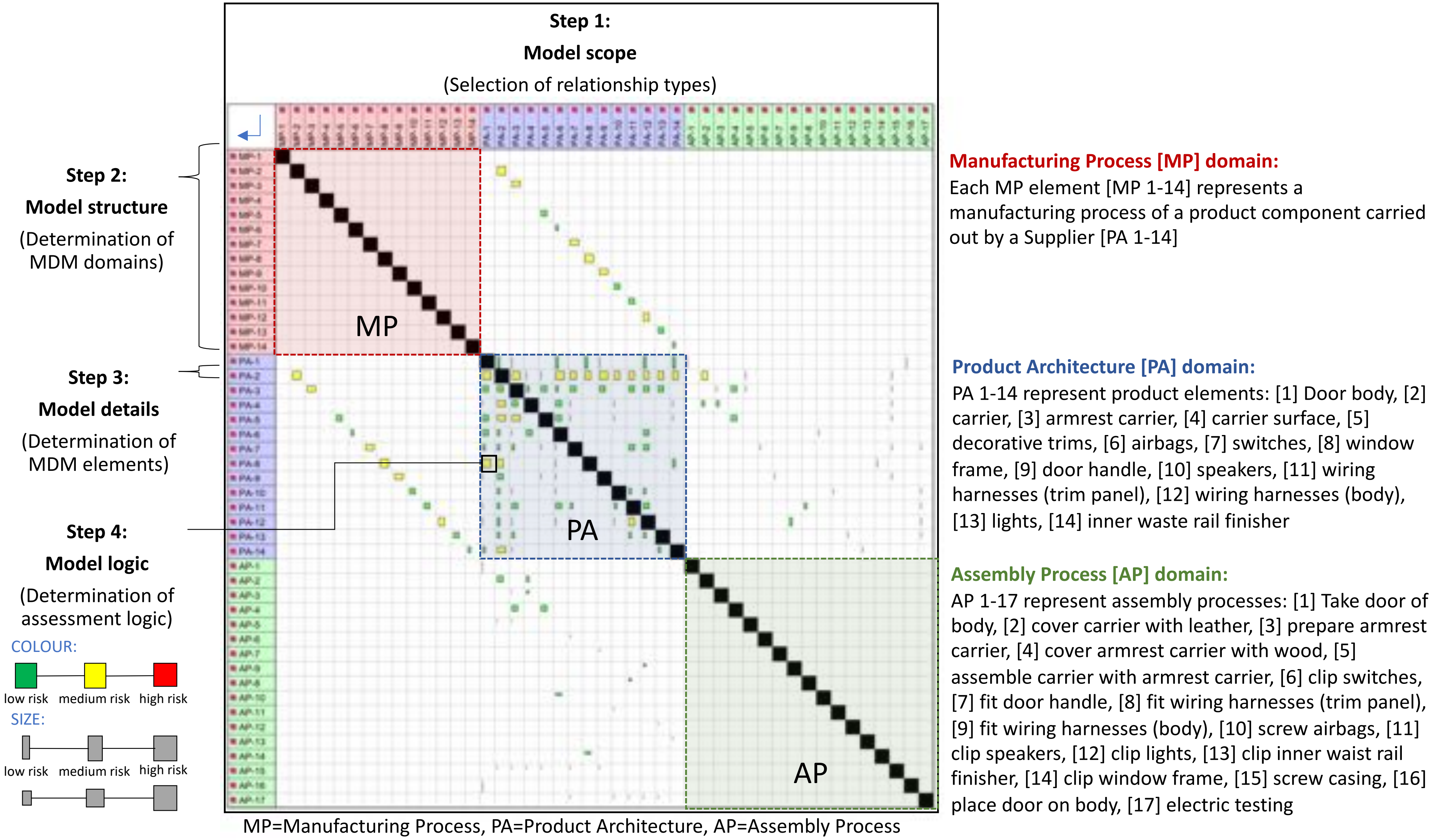
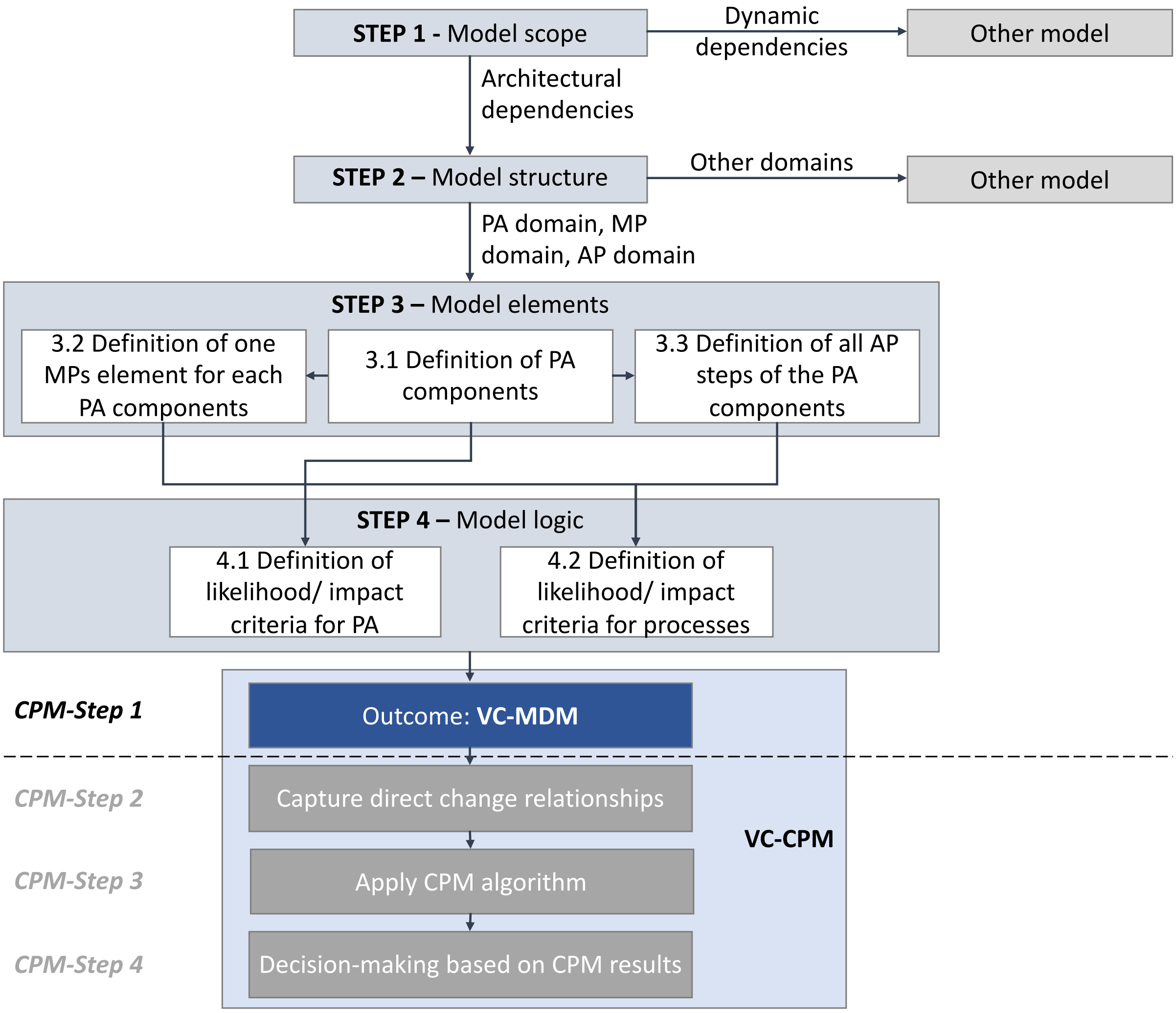


Figure 1: Research methodology based on CPM approach



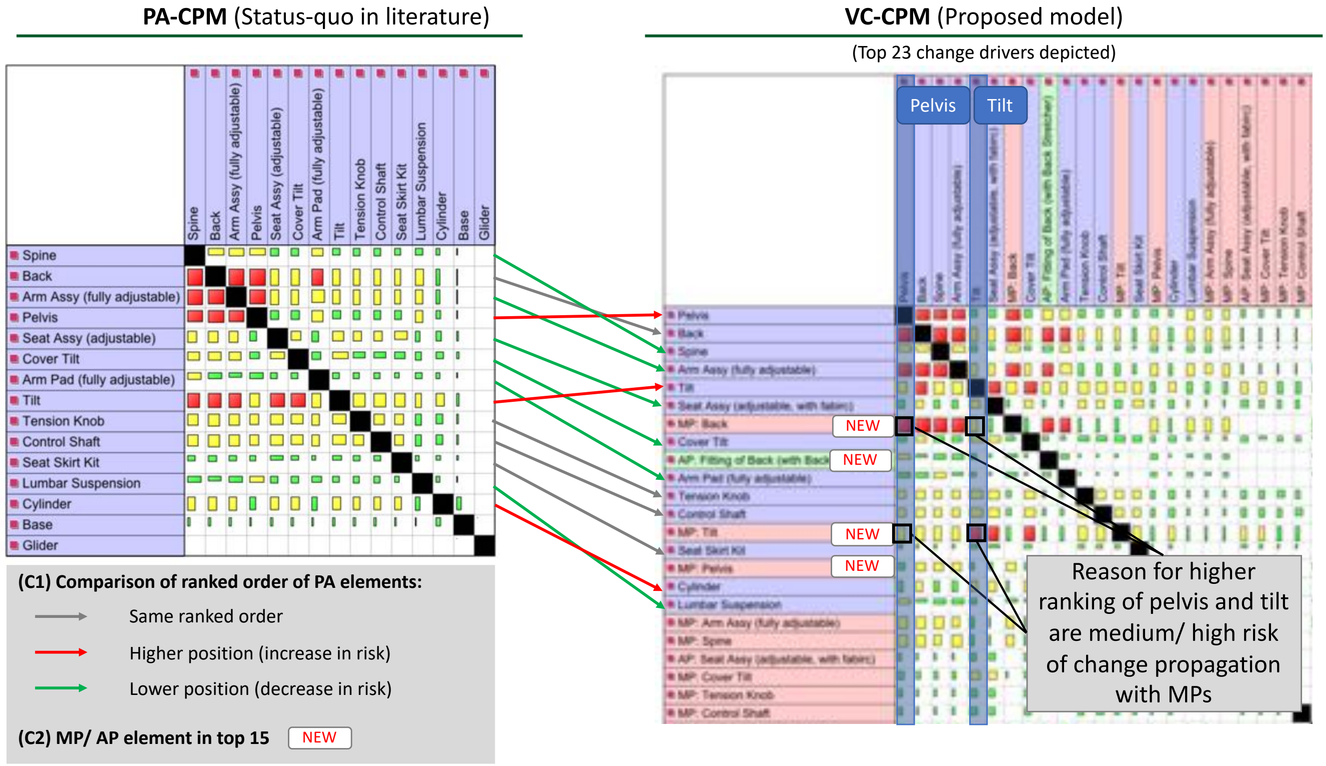
(a) Four-steps to develop the VC-MDM model (top-down) and derived VC-MDM model development representing company A's door trim panel from a VC perspective

Figure 2: Basis of the VC-CPM approach

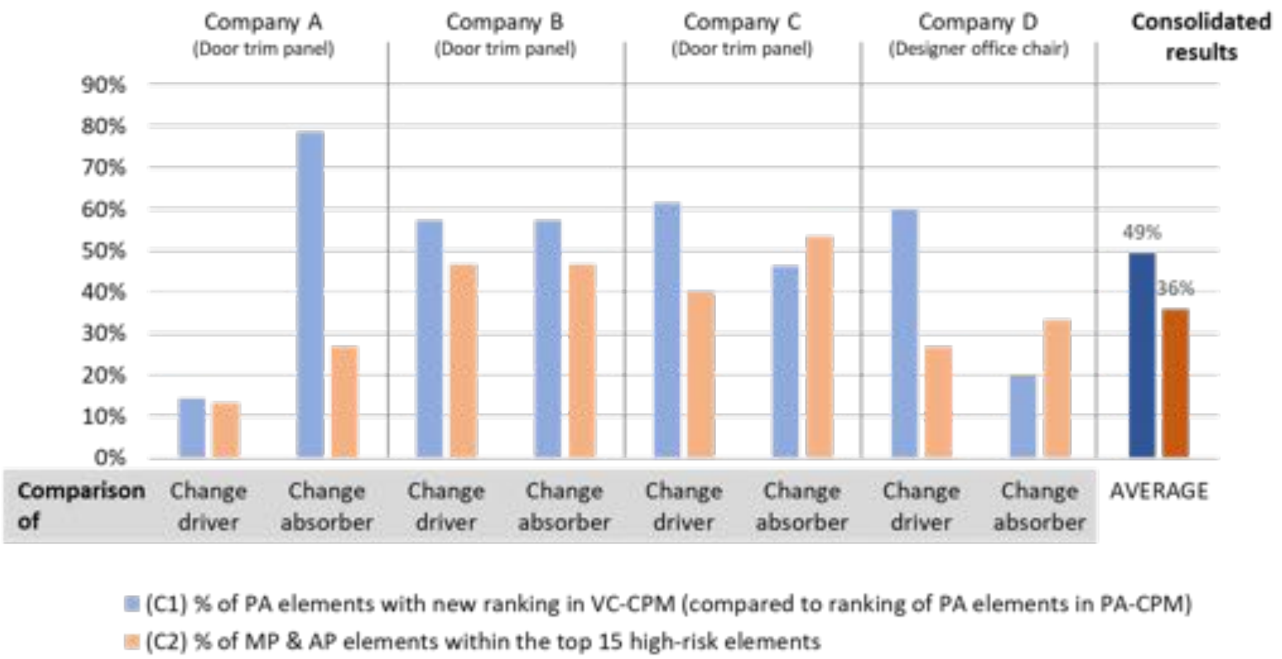


(b) VC-MDM development framework

Figure 2: Basis of the VC-CPM approach



(a) Comparison of PA-CPM (left) with VC-CPM (right) based on change drivers; example from company D



(b) Comparison of VC-CPM and PA-CPM results (based on all four cases)

Figure 3: Comparison of VC-CPM and PA-CPM results

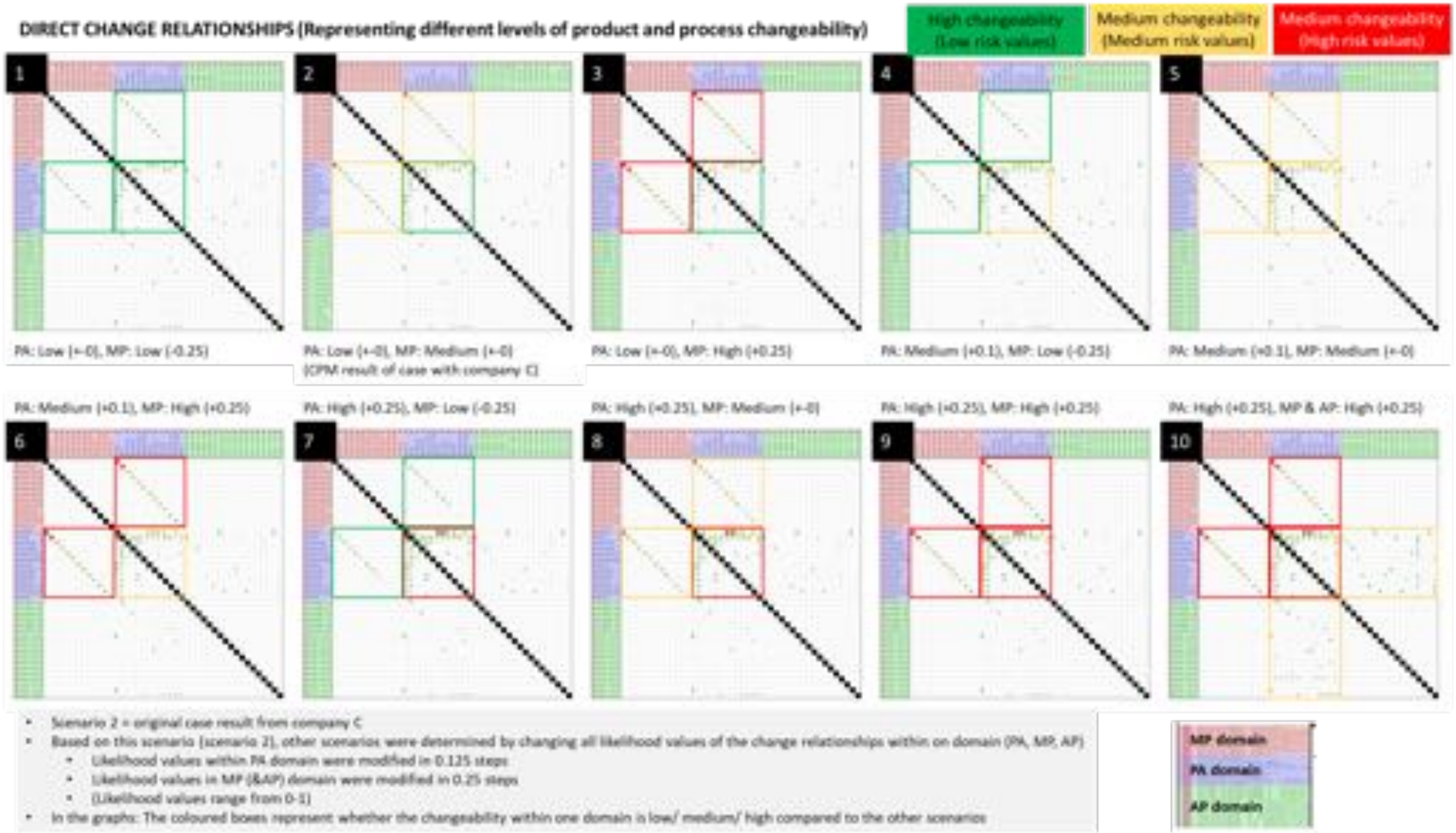


Figure 4: Scenarios with different product (PA) and process (MP, AP) changeability

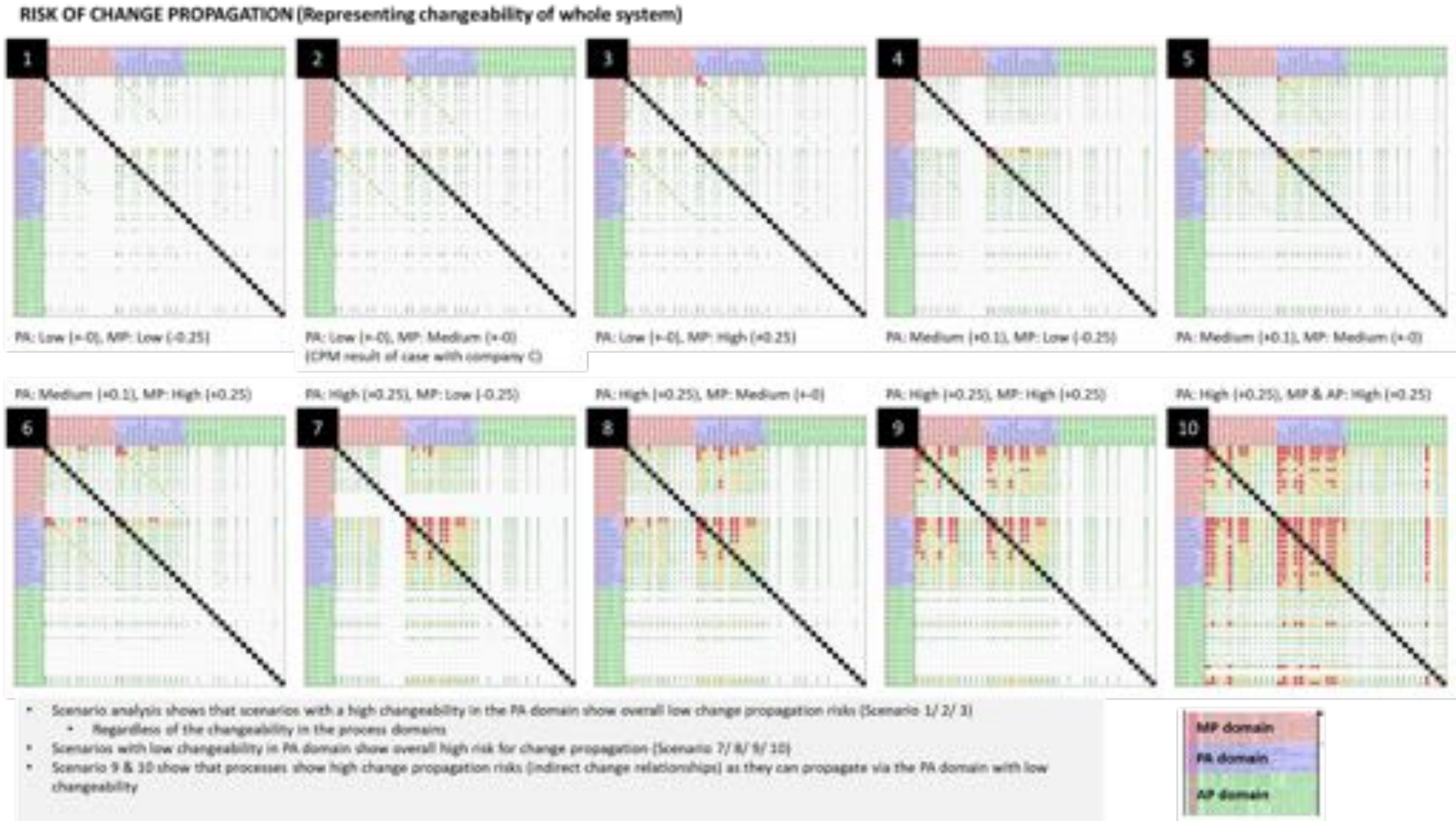


Figure 5: CPM results representing the changeability of the entire VC

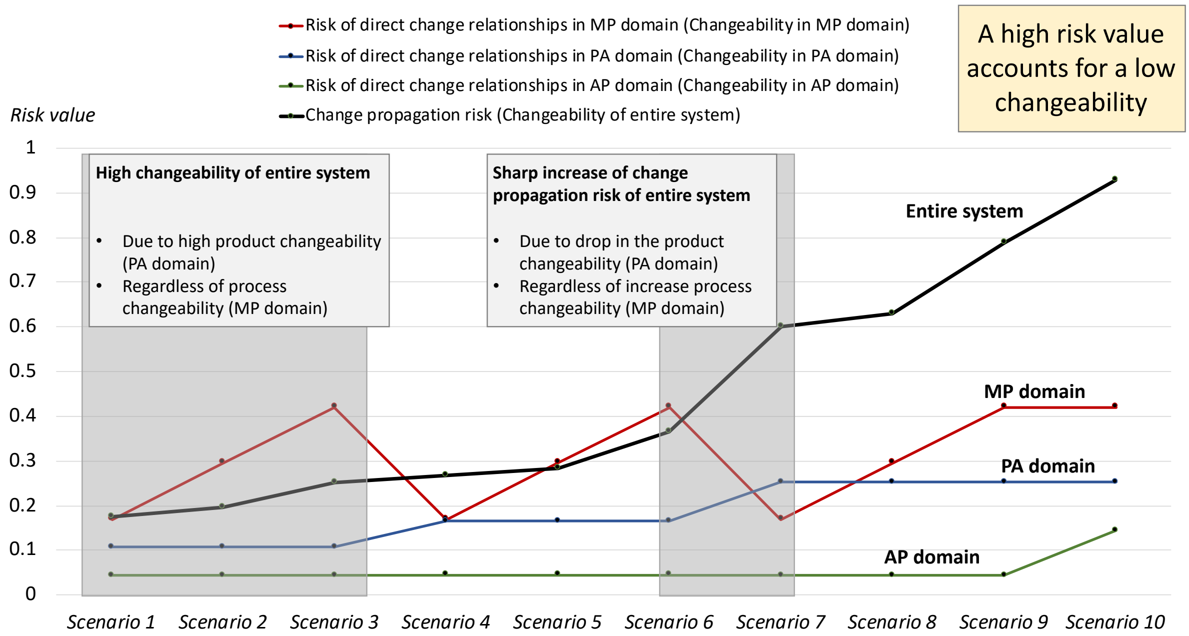


Figure 6: Product changeability as main driver for changeability of entire VC

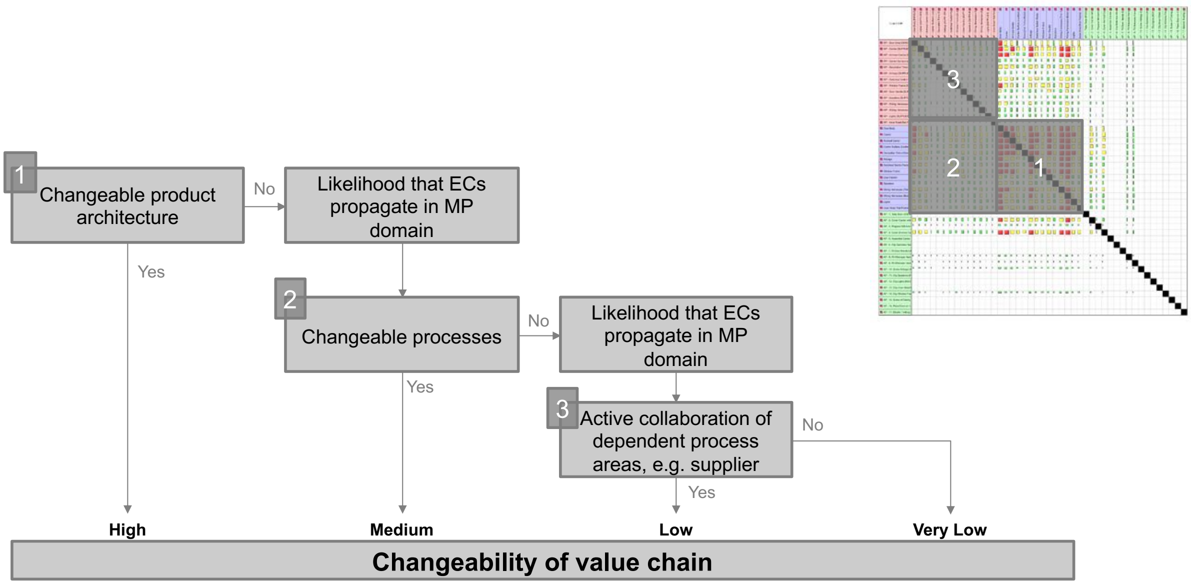
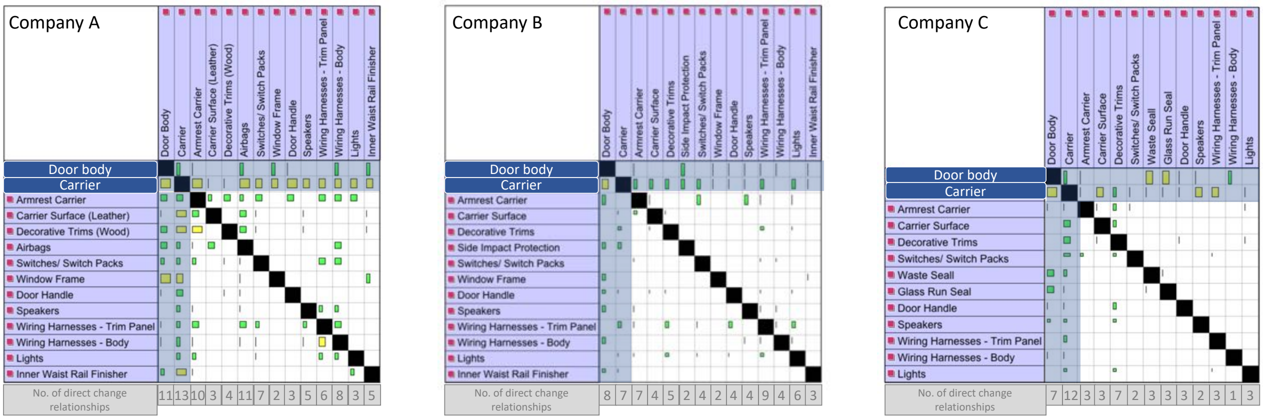
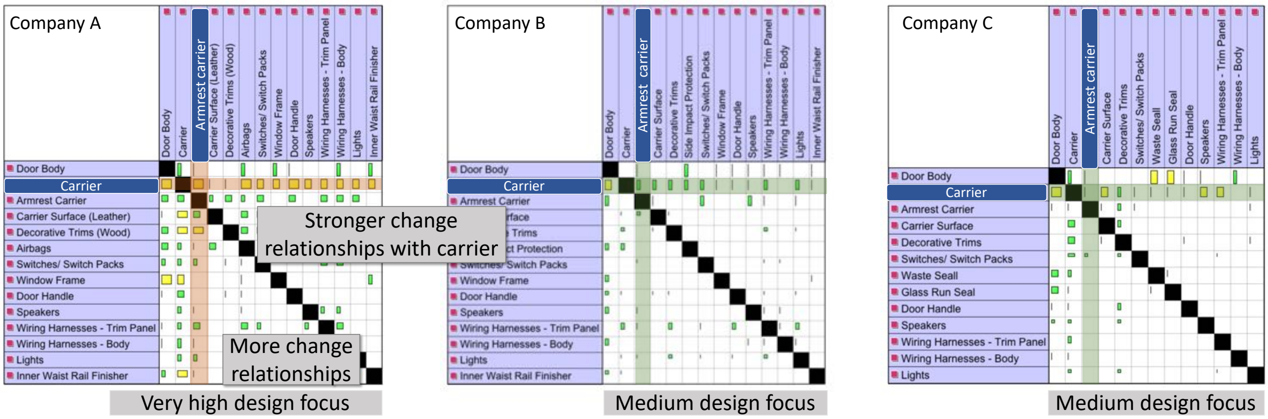


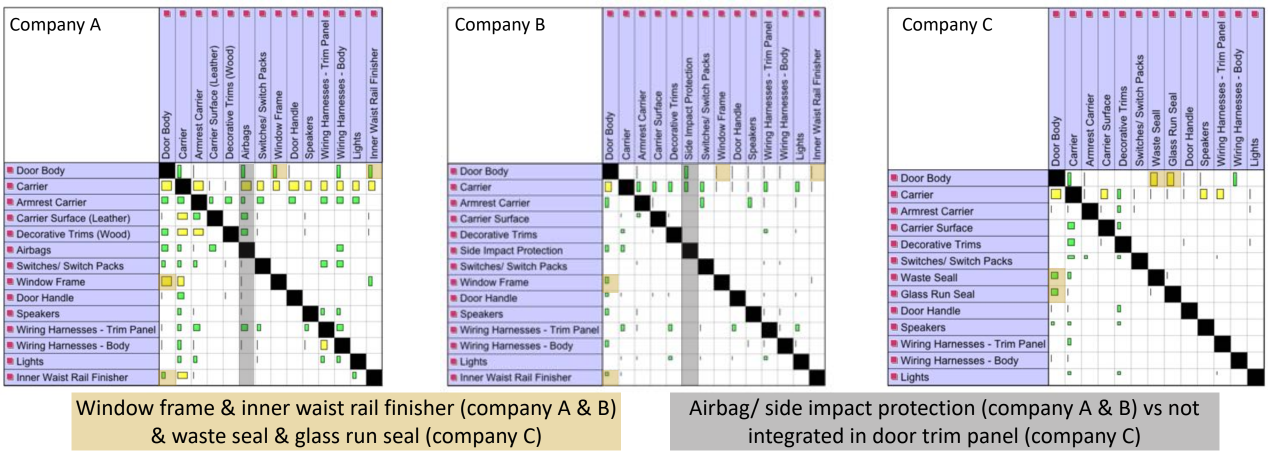
Figure 7: Framework to create a changeable value chain using the VC-CPM



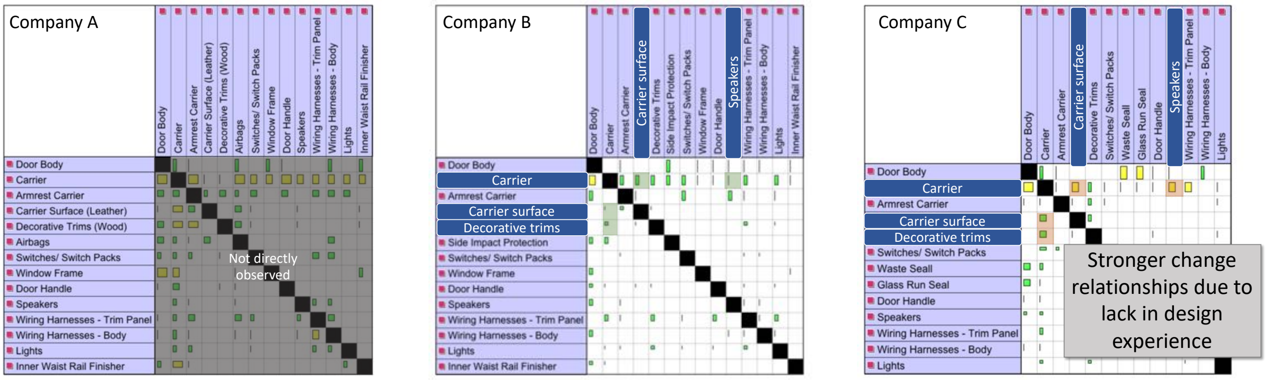
(a) Design concept: High modularity due to carrier as main interface to door



(b) Company A's design focus causes stronger change relationships in the carrier and more change relationships in the armrest carrier



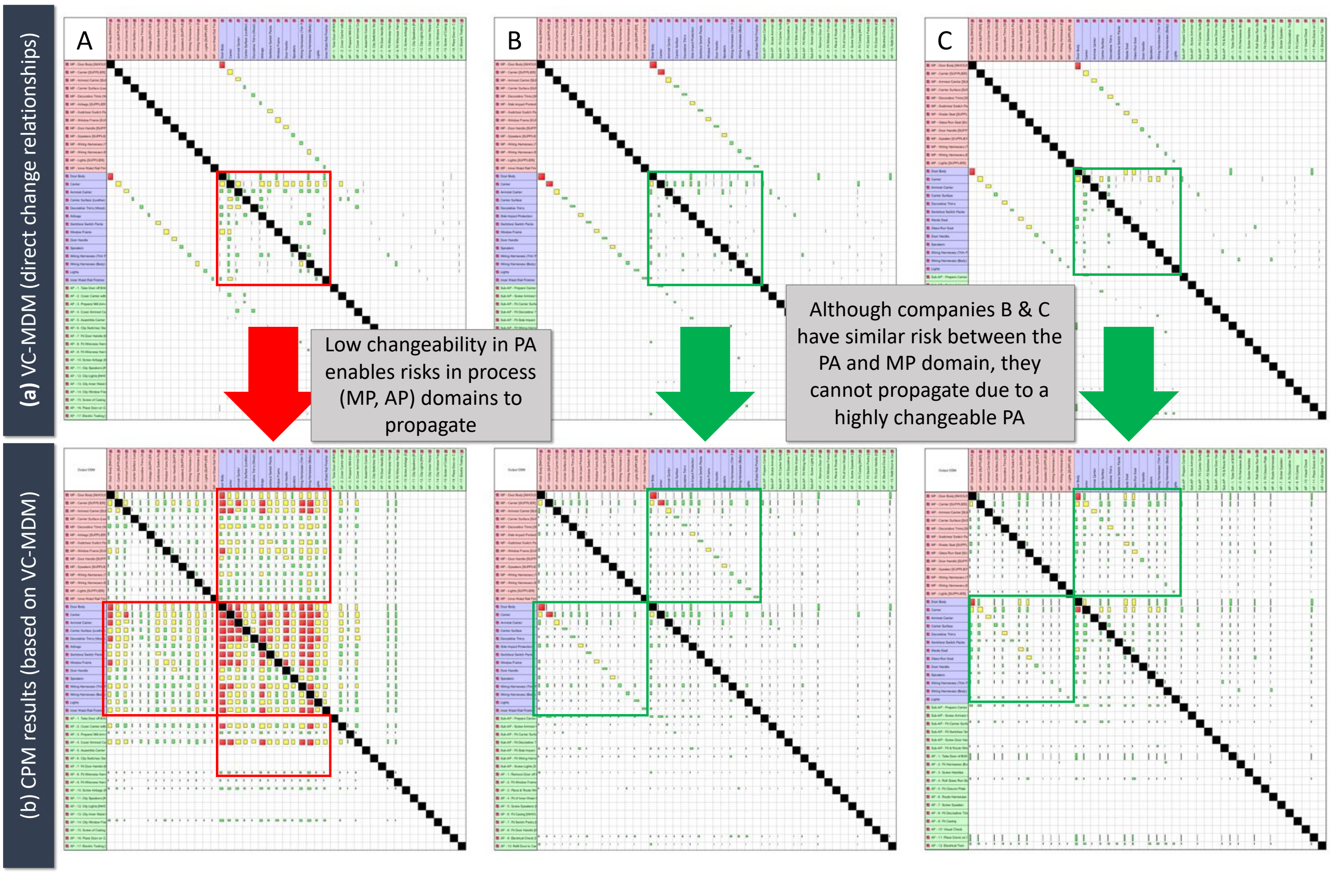
(c) Company C adopts different design solutions by using seals and by not integrating the airbags/ side impact protections into the door trim panel



(d): Lack of standardized interfaces could be caused by a lack of design experience

Figure 8: Analysis of results: Design focus

(a) Cases A, B. C show similar change relationships between the product (PA) and process (MP & AP) domains



(b) Impact of product changeability on change propagation risk in process domains; highest impact in case of company A

Figure 9: Changeability between product domain and process domains

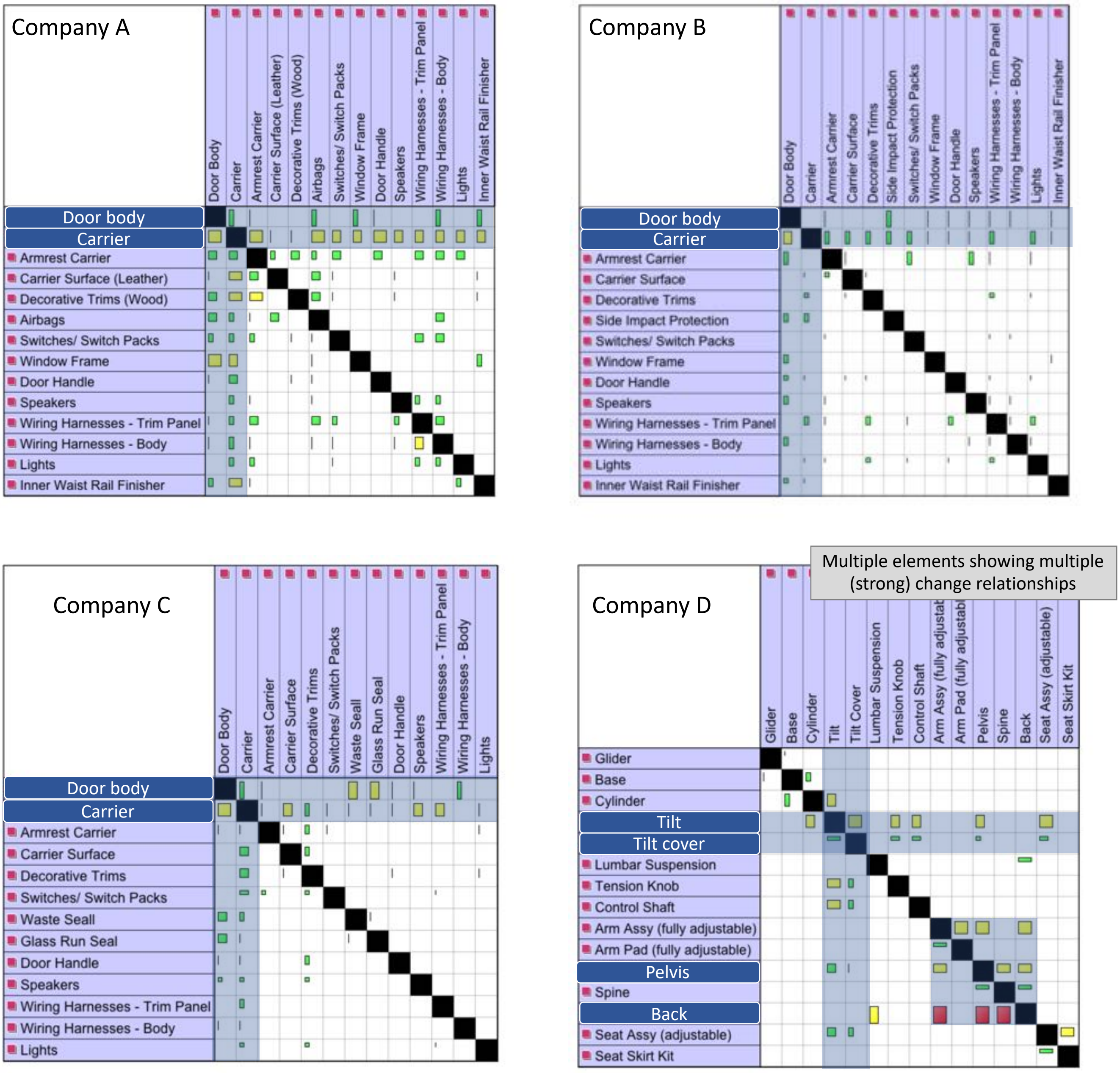
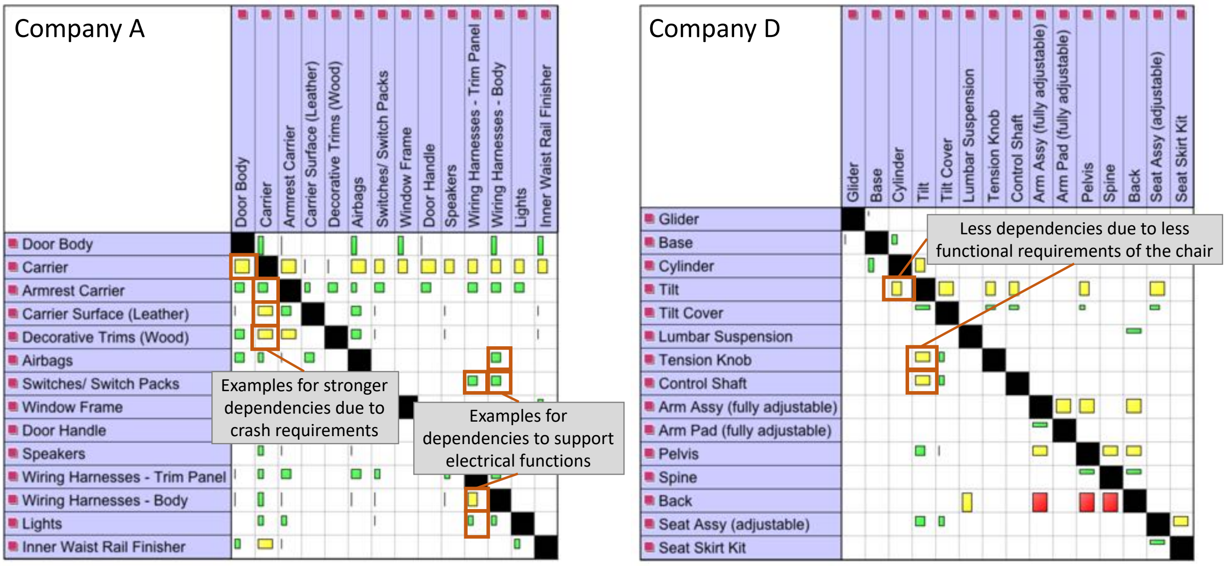
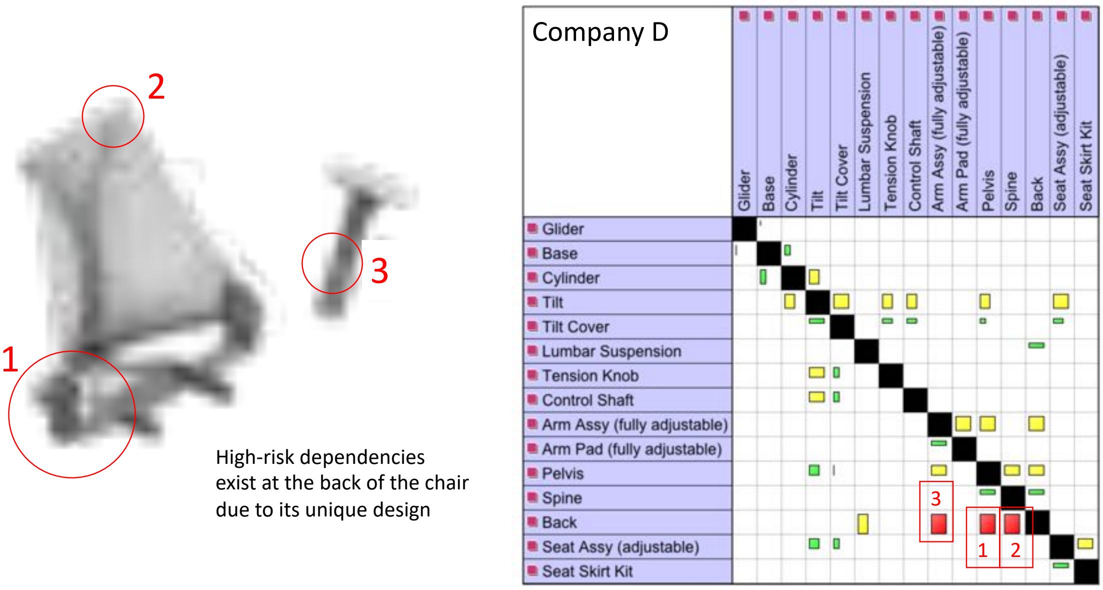


Figure 10: Design concept with multiple core elements used in chair (company D) compared with other cases



(a) Change relationships due to functional requirements



(b) Change relationships due to design focus

Figure 11: Change relationships due to functional requirements and design focus

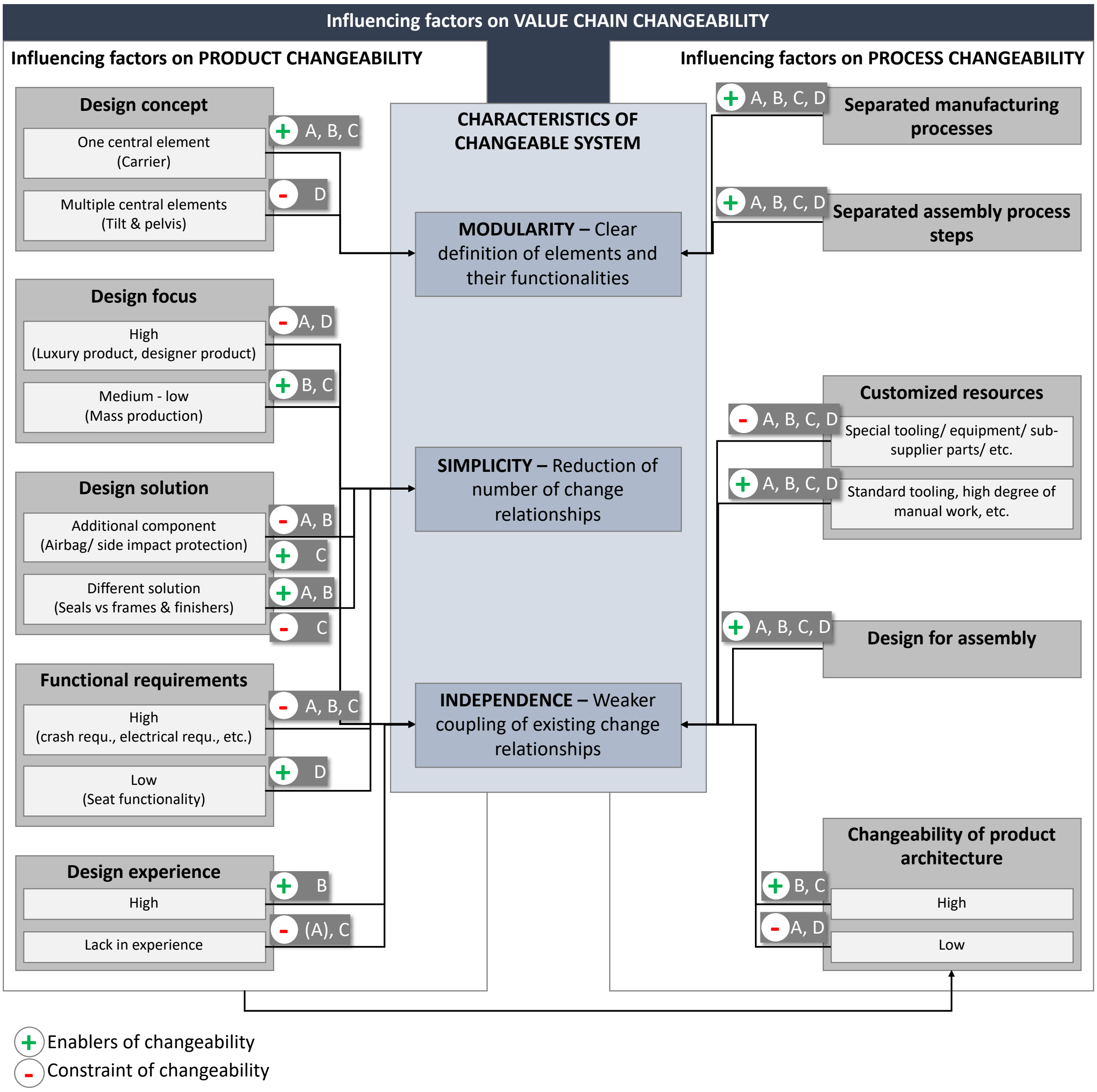


Figure 12: Characteristics/ influencing factors of VC changeability depending on product and process changeability; case specific examples from company A/B/C/D highlighted