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ORIGINAL PAPER

Concepts of change propagation analysis in engineering design

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Abstract

Interest in change propagation analysis for engineering design has increased rapidly since the topic gained prominence in the late 1990s. Although there are now many approaches and models, there is a smaller number of underlying key concepts. This article contributes a literature review and organising framework that summarises and relates these key concepts. Approaches that have been taken to address each key concept are collected and discussed. A visual analysis of the literature is presented to uncover some trends and gaps. The article thereby provides a thematic analysis of state-of-the-art in design change propagation analysis, and highlights opportunities for further work.

Keywords Design change · Change propagation analysis · Key concepts · Literature review · Literature visualisation

1 Introduction

Changes are ubiquitous in engineering design. Design change may be initiated for many reasons, such as to improve a design (Koh et al. 2012), to correct flaws, or to adapt a design to changing requirements (Ahmad et al. 2013). Design change has also been referred to as a source of innovation (Eckert et al. 2004). Design changes can impact any information generated during the product development process. They can occur before or after that information is released. The importance of managing design change is accordingly well-recognised by practitioners and researchers (Fei et al. 2011).

One of the key aspects of design change is that it propagates. In other words, change initiated in one aspect of a design can require knock-on changes for the design to work together as a whole (Eckert et al. 2004; Clarkson et al. 2004; Giffin et al. 2009). Such propagation can be difficult to predict. This is especially the case if the design contains many parts, if design issues are tightly integrated, and/or if knowledge of the design is distributed among multiple specialists or organisations (Ahmad et al. 2013). For this reason, many researchers have developed approaches to change propagation analysis with a view to support change management. There is now a wide variety of approaches and models. However, many draw on similar underlying concepts regarding the nature of change propagation, how it can be modelled and analysed, and how predicting change propagation could support engineering design. This article contributes an organising framework that extracts these underlying key concepts from literature study. In doing so the article provides a thematic summary of current state-of-the-art and an organised source of reference. Some research gaps and opportunities are also identified.

We build on a number of previously published literature reviews of this field. These can be categorised into (1) broad reviews of engineering change management (ECM), (2) focused reviews that focus more narrowly within this area, and (3) reviews of design change propagation models in particular. First, in terms of broad ECM reviews, one of the earliest was published by Wright (1997). Much progress has been made in the decades since. In this journal, Jarratt et al. (2011) provide a highly-cited review of research relevant to ECM. They include a discussion of propagation analysis but do not address this specific subtopic in depth. Again, significant research progress has been made since the review by Jarratt et al. (2011) was published. Other general ECM reviews adopt a bibliometric approach. For instance, Hamraz et al. (2013b) analyse

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427 publications from a "holistic and process-oriented" perspective, covering "not only ECM but also related cross-disciplinary areas" (Hamraz et al. 2013b). Barroso and de Andrade Júnior (2018) present a less comprehensive bibliometric analysis of 62 ECM publications. While clarifying trends, these bibliometric reviews of ECM do not analyse concepts in depth. Finally, a number of PhD dissertations relating to engineering change and its management incorporate broad reviews of the ECM literature (e.g. Jarratt 2004; Koh 2010; Hamraz 2013).

Second, highly focussed reviews each treat selected aspects of engineering change management. Shapiro et al. (2015) identify and review papers related to design process changes, classifying them according to whether they focus on change effects in terms of (1) change in activities; (2) change in deliverables; or (3) changes that impact the relationships between activities and/or deliverables. Chucholowski et al. (2013) concentrate on reviewing the related topic of change cause analysis, while Karthik and Reddy (2016) present a comparative analysis of configuration management and change management. More recently, Tale-Yazdi et al. (2019) review data analysis approaches in ECM, broadly categorising publications based on their use of either a-priori or a-posteriori analysis approaches.

Third, and most relevant to this article, some reviews focus specifically on change propagation analysis (CPA). Ahmad et al. (2011) consider CPA methods published in Design Society conferences between 2005 and 2010, developing a categorisation of the approaches based on the different information models used by each approach. Helms et al. (2014) look more closely at 11 papers proposing CPA methods. Ullah et al. (2016) review CPA papers published after September 2011, including a citation analysis. These authors broadly categorise methods under product, process and people domains. Finally, in this group of reviews, Masmoudi et al. (2018) classify CPA research work according to whether it is based on a theoretical dependency model or an a-posteriori dependency model.

The present article contributes to the third category discussed above, in particular by presenting a detailed and thematic review of change propagation analysis (CPA) in the engineering design context. It may be noted that the previous literature reviews in this category (as described in the previous paragraph) are short conference papers and focus on reviewing and comparing contributions on a publication-by-publication basis. This article adds insight by introducing an organising framework that clarifies the key concepts that appear in literature. Additionally, a visual analysis of the literature is presented to show how the concepts are brought together in research publications. Overall the article is intended to provide an overview of current thinking in the area, to provide an organised source of reference, and to assist researchers in positioning future work.

2 Framework for organising the key concepts of change propagation analysis

A framework was created to organise the key concepts relating to change propagation analysis, that were revealed through literature review. The scope of the review was set on computable models to support change propagation analysis in the engineering design context. Other aspects of design change management, such as change propagation in non-engineering design domains such as software and construction, and processes or strategies for managing engineering change, were considered out-of-scope. To identify models to be reviewed, the list of 23 propagation models presented by Ahmad et al. (2013) was used as a starting point. This was integrated with the list of 54 methods collected in Hamraz et al. (2013c). After filtering to remove duplicates and items outside the scope, the broader literature was then searched for additional models that had been overlooked or had been published since the reviews mentioned above were compiled. First, the bibliographies of publications in the emerging list were studied to find further sources. Second, work that cited publications in the list was identified using Google Scholar and Scopus. Finally, the list of journals was extracted and each of these journals was investigated for further relevant work.

In parallel to the search, an organising framework of key concepts was created. Each identified publication was analysed and aligned against the emerging framework. This led to iterative improvements until the framework was able to account for key concepts in all the reviewed work. Because the objective of this article is to clarify and organise key concepts, not to exhaustively list all relevant publications, the bibliography was finally pruned for conciseness and clarity.

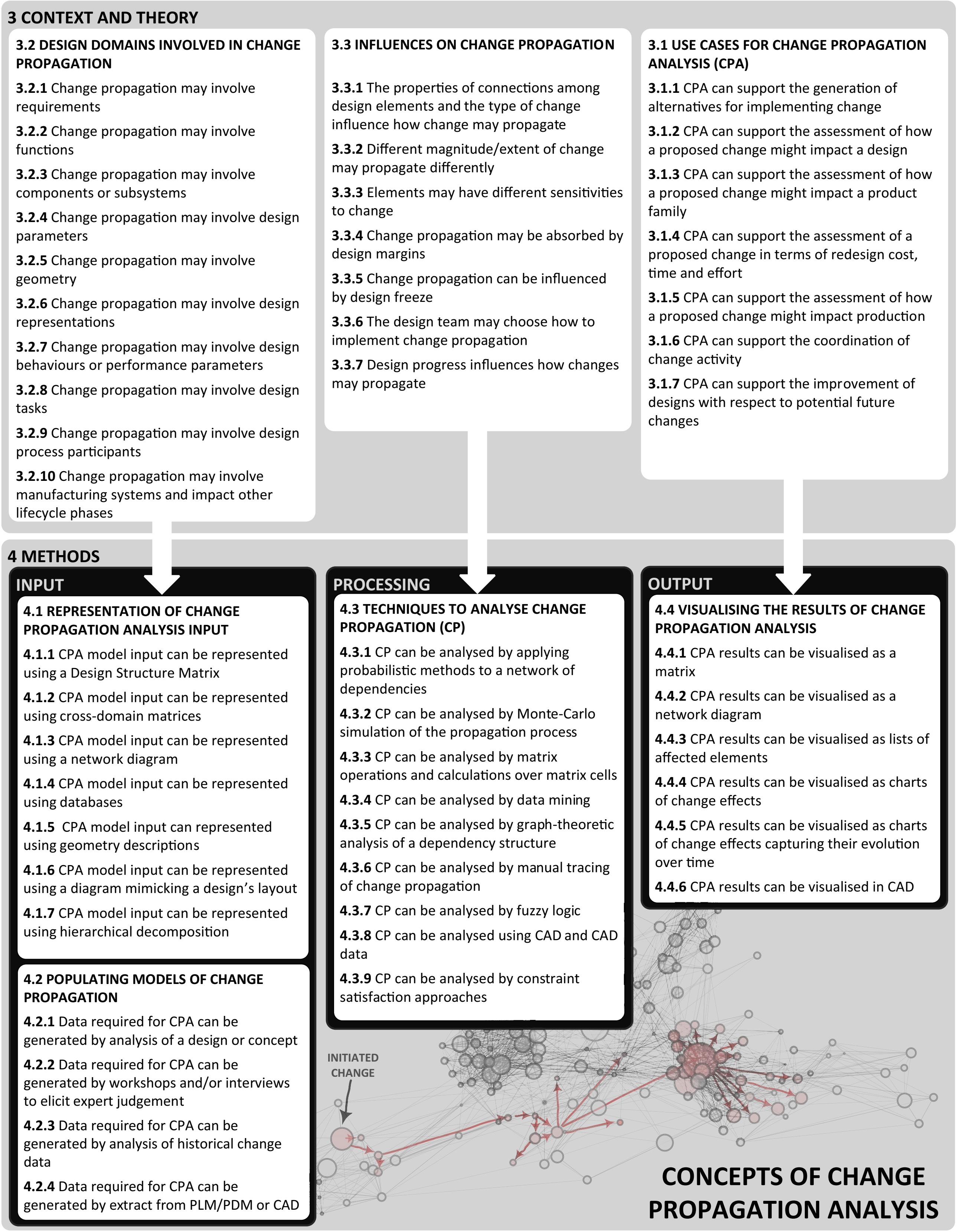
The literature search also supported the objectives of this article by confirming that a comprehensive synthesis of key concepts in change propagation analysis has not previously been published.

2.1 Overview of the organising framework

The organising framework is depicted in Fig. 1. It summarises research on change propagation analysis as a set of *key concepts* (shown as bullet points) that are organised into *categories* (shown as boxes).

The first set of categories, shown in the top row of Fig. 1, relate to the context and theory of change propagation analysis (CPA):

- *Use cases for change propagation analysis* concern how CPA can be applied and how it may provide support for practice.



3 CONTEXT AND THEORY

3.2 DESIGN DOMAINS INVOLVED IN CHANGE PROPAGATION

3.2.1 Change propagation may involve requirements

3.2.2 Change propagation may involve functions

3.2.3 Change propagation may involve components or subsystems

3.2.4 Change propagation may involve design parameters

3.2.5 Change propagation may involve geometry

3.2.6 Change propagation may involve design representations

3.2.7 Change propagation may involve design behaviours or performance parameters

3.2.8 Change propagation may involve design tasks

3.2.9 Change propagation may involve design process participants

3.2.10 Change propagation may involve manufacturing systems and impact other lifecycle phases

3.3 INFLUENCES ON CHANGE PROPAGATION

3.3.1 The properties of connections among design elements and the type of change influence how change may propagate

3.3.2 Different magnitude/extent of change may propagate differently

3.3.3 Elements may have different sensitivities to change

3.3.4 Change propagation may be absorbed by design margins

3.3.5 Change propagation can be influenced by design freeze

3.3.6 The design team may choose how to implement change propagation

3.3.7 Design progress influences how changes may propagate

3.1 USE CASES FOR CHANGE PROPAGATION ANALYSIS (CPA)

3.1.1 CPA can support the generation of alternatives for implementing change

3.1.2 CPA can support the assessment of how a proposed change might impact a design

3.1.3 CPA can support the assessment of how a proposed change might impact a product family

3.1.4 CPA can support the assessment of a proposed change in terms of redesign cost, time and effort

3.1.5 CPA can support the assessment of how a proposed change might impact production

3.1.6 CPA can support the coordination of change activity

3.1.7 CPA can support the improvement of designs with respect to potential future changes

4 METHODS

INPUT

4.1 REPRESENTATION OF CHANGE PROPAGATION ANALYSIS INPUT

4.1.1 CPA model input can be represented using a Design Structure Matrix

4.1.2 CPA model input can be represented using cross-domain matrices

4.1.3 CPA model input can be represented using a network diagram

4.1.4 CPA model input can be represented using databases

4.1.5 CPA model input can represented using geometry descriptions

4.1.6 CPA model input can be represented using a diagram mimicking a design's layout

4.1.7 CPA model input can be represented using hierarchical decomposition

4.2 POPULATING MODELS OF CHANGE PROPAGATION

4.2.1 Data required for CPA can be generated by analysis of a design or concept

4.2.2 Data required for CPA can be generated by workshops and/or interviews to elicit expert judgement

4.2.3 Data required for CPA can be generated by analysis of historical change data

4.2.4 Data required for CPA can be generated by extract from PLM/PDM or CAD

PROCESSING

4.3 TECHNIQUES TO ANALYSE CHANGE PROPAGATION (CP)

4.3.1 CP can be analysed by applying probabilistic methods to a network of dependencies

4.3.2 CP can be analysed by Monte-Carlo simulation of the propagation process

4.3.3 CP can be analysed by matrix operations and calculations over matrix cells

4.3.4 CP can be analysed by data mining

4.3.5 CP can be analysed by graph-theoretic analysis of a dependency structure

4.3.6 CP can be analysed by manual tracing of change propagation

4.3.7 CP can be analysed by fuzzy logic

4.3.8 CP can be analysed using CAD and CAD data

4.3.9 CP can be analysed by constraint satisfaction approaches

OUTPUT

4.4 VISUALISING THE RESULTS OF CHANGE PROPAGATION ANALYSIS

4.4.1 CPA results can be visualised as a matrix

4.4.2 CPA results can be visualised as a network diagram

4.4.3 CPA results can be visualised as lists of affected elements

4.4.4 CPA results can be visualised as charts of change effects

4.4.5 CPA results can be visualised as charts of change effects capturing their evolution over time

4.4.6 CPA results can be visualised in CAD

Fig. 1 Framework organising the key concepts of change propagation analysis. Numbers refer to the sections of this article in which the corresponding concepts are discussed

- *Design domains involved in change propagation.* A fundamental idea in CPA is that change propagates among discrete elements in the design environment, e.g. between components of the design. Key concepts in this category concern the types of element and the ways in which change can propagate among them.
- *Influences on change propagation* concern conceptual models of why design change either propagates or is absorbed in specific cases.

The second set of categories, depicted in the bottom row of Fig. 1, relate to models and approaches for analysing change propagation:

- *Representation of input data required for CPA* concerns how the data required for CPA can be represented and visualised, for instance, using a dependency structure matrix, network diagram, or other approach.
- *Population of input data required for CPA* concerns how the information required for CPA can be obtained, for instance, by data mining, practitioner workshops, and so on.
- *Techniques to analyse change propagation* concern the approaches used to predict how change may propagate in a particular design situation, for instance, matrix computations, Monte-Carlo simulation and others.
- *Representation of CPA results* concerns how the output from a CPA model can be visualised to convey insight for practice.

The next sections discuss these seven categories and the corresponding key concepts one-by-one. After completing discussion of the key concepts, the body of literature is analysed more holistically in Sect. 5. Research gaps and suggestions for future work are discussed in Sect. 6.

3 Key concepts relating to the context and theory of change propagation analysis

3.1 Use cases for change propagation analysis

Change propagation analysis (CPA) can support different facets of the engineering change management (ECM) process. Seven use cases for CPA were identified in the literature, as depicted in the top-right cell of Fig. 1 and discussed in the rest of this subsection.

Our discussion of CPA use cases is organised according to the model of the ECM process developed by Jarratt et al. (2004). Their model divides the ECM process into three phases:

1. The *first phase* comprises steps that take place before approval of a change request. A request to introduce changes to previously released design work is raised. Alternative possible solutions to the change request are then generated, after which risk and impact assessments of the solutions are undertaken.
2. The *second phase* comprises steps that take place during approval of a change request. The change request is formally reviewed. Then, a selection between proposed solutions may be made and approval for the change granted.
3. The *third phase* comprises steps that take place after approval of a change. The design change is implemented, after which the process is reviewed to document the outcome and lessons learnt.

Use cases for CPA that are discussed in the literature were aligned against these phases and their constituent steps, as depicted in Fig. 2. The figure indicates that CPA can support most steps in the Jarratt et al. (2004) model. In addition, Fig. 2 shows that CPA can help to inform design improvements with respect to future changes. The use cases are each discussed in the next subsections.

3.1.1 CPA can support the generation of alternatives for implementing a change

A desired change can often be addressed by multiple design solutions. In line with best practices for engineering design (e.g. Pahl and Beitz 2013) generating a broad range of change solutions for comparison is recommended to improve the likelihood of finding a good solution. Applying this principle to support Step 2 in Fig. 2, CPA can be used to propagate change from a requirement or function to the various parts that realise it and hence, can help shortlist parts that could potentially be modified to accommodate that change (Ahmad et al. 2013).

3.1.2 CPA can support the assessment of how a proposed change might impact a design

When one part of a design is changed, it is likely that other parts will also have to be modified so they can continue to work together properly (Eckert et al. 2004). Considering Step 3 of Fig. 2, a key challenge when assessing the risk and impact of a proposed change is to appreciate these potential knock-on effects. Researchers have argued that CPA can support this in several ways:

- Change propagation may cause risks to product integrity because some knock-on effects may not be foreseen and accounted for. CPA can help manage such risks by gener-

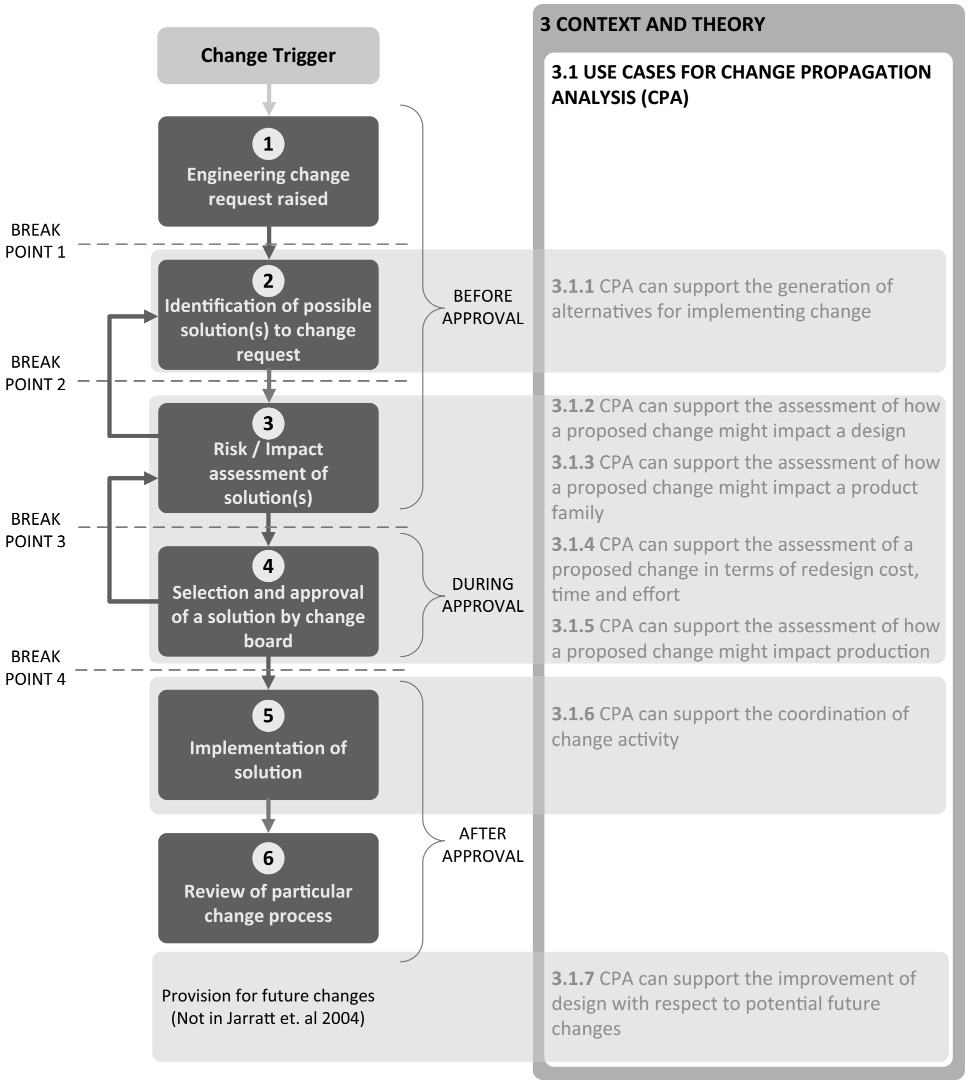


Fig. 2 Use cases for Change Propagation Analysis (CPA) aligned against steps of the engineering change management process as described in the model of Jarratt (2004), shown on the left hand side. Numbers on the right hand side refer to subsections in which each use case is discussed. Process model shown on the left hand side is redrawn from Jarratt (2004) with permission of the author

ating a better appreciation of the possible impact of each change (Hamraz et al. 2012; Yang and Duan 2012).

- Designers can find change propagation in complex products overwhelming, which might lead to overlooking potential knock-on effects (Keller et al. 2005). A systematic CPA method could help to avoid this (Clarkson et al. 2004).
- Products are typically designed by multi-disciplinary teams, and identification of possible propagation across disciplinary boundaries may be difficult (Reddi and Moon 2009). A systematic CPA method could help to comprehensively identify and trace change propagation, reducing the reliance on discussion among engineers when assessing change impact.
- Where there are several change options under consideration to improve design performance, CPA can help to choose between them by highlighting how interactions within the design might support or cancel out the initiated change (Koh et al. 2012). CPA may also help to identify the change options whose propagation might involve the smallest number of steps (Ma et al. 2016).

3.1.3 CPA can support the assessment of how a proposed change might impact a product family

To offer products that are tailored to the needs of specific market segments and that can be developed and manufactured competitively, many companies generate families of closely related products (Simpson 2004; Cheng et al. 2019). In a product family context, risk and impact assessment of a proposed change needs to consider whether resources impacted by the change are shared across several product variants (Raffaeli et al. 2007, 2013; Ullah et al. 2017a). The assessment should consider whether relationships among the product family might expand the scope of the redesign, or may undesirably reduce commonality across the product family. CPA that is aware of the product family architecture can assist with these tasks.

3.1.4 CPA can support the assessment of a proposed change in terms of redesign cost, time and effort

To complete a risk and impact assessment of a proposed change, the schedule, effort and resource implications must be considered (Li and Zhao 2014; Li et al. 2015, 2012, 2018; Yeasin et al. 2019). These implications depend on the extent to which the change might propagate (Eckert et al. 2004). CPA could, therefore, assist with assessing redesign efforts (Chen et al. 2007; Li and Chen 2007, 2010) and costs (Roser et al. 2003; Chen et al. 2007; Siddharth and Sarkar 2018; Li et al. 2020) associated with alternative change options. It could also help to assess how a design change might disrupt the schedule of an ongoing design project, depending on the scope of the change and the point in the project at which it is implemented (Chua and Hossain 2012). Finally, in this subsection, CPA could help to determine an appropriate cutoff date after which additional design changes should not be accepted, because of the increased cost, effort and duration that arises from the need to rework more activities when a change occurs later in a project (Chua and Hossain 2012).

3.1.5 CPA can support the assessment of how a proposed change might impact production

Design changes impact manufacturing processes and systems (Plehn et al. 2016; Yin et al. 2016; Siddharth and Sarkar 2017; Albers et al. 2021). Research suggests that CPA could help assess this impact in several ways:

- CPA could help to trace how design change would lead to changes in the supply chain, e.g. parts which have already been procured, rendering unused inventory items obsolete (Ho and Li 1997).
- Design changes may impact parts that have already been partially manufactured. CPA could identify such parts earlier in the ECM process, potentially saving time and effort in reprocessing (Leng et al. 2016; Ouertani et al. 2004).
- CPA could identify how manufacturing machines might need to be adapted in response to a design change in the parts being manufactured (Hoang et al. 2017b, a).
- CPA could help assess how change propagates within a manufacturing system, and how this might affect performance metrics such as throughput or equipment effectiveness (Bauer et al. 2017).
- CPA could help to assess how design changes cause knock-on changes to manufacturing operations, and how this might require redistribution of those operations across plants (Tseng et al. 2008).

3.1.6 CPA can support the coordination of change activity

Moving onto Step 5 of the ECM model depicted in Fig. 2, once the assessment of a proposed design change is completed and a change option has been selected for implementation, completing the redesign work requires management of the dependencies between the change and the rest of the design context. Literature suggests that CPA could support this coordination in the following ways:

- Design changes to individual parts can create inconsistencies unless propagated to related parts in an assembly. CPA may help to identify the affected components and assembly relationships, thereby helping to maintain consistency in design data (Eltaief et al. 2017, 2018).
- CPA may help to ensure changes to component designs are propagated to all the data views used by collaborating teams (Do et al. 2008).
- Teams collaborating across organisations may use different CAD/CAM/CAE/PLM platforms which creates additional challenges in managing data consistency. CPA may be used to support development of models which maintain consistency across multiple platforms (Hwang et al. 2009; You and Chao 2009).
- As noted in the previous subsection, changes in design also require changes in manufacturing. Relating to coordination, inconsistency in product data caused by design changes may trigger knock-on inconsistencies in the manufacturing system. CPA can support coordination between design and manufacture by systematically updating the downstream data following design change (Leng et al. 2016).

3.1.7 CPA can support the improvement of designs with respect to potential future changes

CPA has also been applied to enhance changeability, which has been defined as the ease with which a system can undergo various changes, or the degree to which it is insensitive towards those changes (Schulz et al. 2000; Ross et al. 2008):

- Increased modularity may suppress change propagation and hence improve changeability (Ulrich and Eppinger 2003; Sarica and Luo 2019). CPA can be used to pinpoint components at high risk of change. Such components might be suitable targets for modularisation (Koh et al. 2015).
- Designing flexibility into a product platform can make it easier to generate a planned family of variants, and can make it easier to respond to potential future changes in market demand. CPA can help to identify which parts of the product family would especially ben-

efit from being made flexible, because the flexibility would suppress knock-on effects of necessary changes (Suh et al. 2007). Similarly, if a platform is to be generated by allowing certain parameters of a design to be scaled, CPA can help to determine which parameters could be modified to create a desired range of products while not strongly impacting other parameters (Schuh et al. 2017).

- Propagation analysis can be used to identify where margin should be placed in a design to absorb potential future change (Brahma and Wynn 2020; Long and Ferguson 2021).

3.2 Design domains involved in change propagation

A design and its context can be viewed and decomposed from several perspectives, such that analyses in different domains are possible (see, e.g. Eder and Hosnedl 2010; Andreasen 2011). For example, a design can be considered in the function domain, in the component domain, and in other domains. Change propagation analysis addresses the use cases of Sect. 3.1 through the fundamental concepts that (1) a design and its context can be decomposed into discrete elements in one or more domains, and (2) change propagates among these elements. As depicted in the top-left cell of Fig. 1, ten domains considered important to change propagation analysis were identified from the literature review. These are discussed in Sects. 3.2.1–3.2.10.

3.2.1 Change propagation may involve requirements

Requirements are essential points of reference throughout the design process (Ulrich and Eppinger 2003) and are also one of the main initiators of design changes (Ahmad et al. 2013; Gräßler et al. 2019, 2020). Requirement change is especially common in the early stages of the design process where there is much uncertainty (Becerril et al. 2016) and also occurs during later design iterations (Tang et al. 2016). Regardless of the timing and cause of requirement changes, they necessitate modification to the design itself, which is a form of change propagation (Ahmad et al. 2013). Changes to a design that are introduced so it can address one modified requirement can interfere with that design's ability to meet other requirements (Koh et al. 2012). Change can also propagate among requirements that concern the same engineering issues, such as vibration, or that are related hierarchically (Morkos et al. 2012). Overall, foreseeing the propagation of requirement change is important so that a company can decide whether a proposed change should be accepted or not (Yu et al. 2017).

3.2.2 Change propagation may involve functions

In the context of CPA, functions have been defined as descriptions of the intended purpose of a design or of parts of that design (Hamraz et al. 2012). Functions are important in change propagation because they establish a link from some (but not all) requirements to components that realise them (Ahmad et al. 2013; Kattner et al. 2017; Wilms et al. 2020). Since a change can only be implemented on a physical realisation (Koh 2017), when a change in functionality is required this causes knock-on change to the parts that realise it (Masmoudi et al. 2017a, b). In turn, this can propagate to cause other, possibly undesired functional changes (Flanagan et al. 2003; Fei et al. 2011; Wang et al. 2019). Functions are often realised by collections of parts and their interfaces and hence, change to a function may propagate to require changes in how parts interact (Albers et al. 2011). For example, power transmission in a gear reducer involves the interfaces between pairs of meshing gears. Ultimately, the functions that a design must provide influence decisions on many properties such as material, manufacturing process, tolerances and so on (Joshi et al. 2005), such that changes to function potentially propagate to affect these properties as well.

3.2.3 Change propagation may involve components or subsystems

Identification of components that are directly or indirectly affected by an engineering change is an important task in ECM (Reddi and Moon 2009). Changes can directly propagate between components that are physically connected or connected by other means such as by flows of energy, material or information (Jarratt et al. 2004). Change in a component logically entails change in the subassembly of which it is a part, and vice versa (Ho and Li 1997).

3.2.4 Change propagation may involve design parameters

Change propagation can also involve design parameters, in this context referring to those parameters that are set by the designer. Examples of parameters involved in change propagation are those that define the shape and structure of a product (Zheng et al. 2017; Rios-Zapata et al. 2017; Zheng et al. 2020; Bashir and Ojiako 2020) such as dimensions and material specifications (Koh et al. 2012). Parameters in other design domains such as process, labour, cost, material, etc. can also be involved in propagation (Siddharth and Sarkar 2017).

Dependencies among design parameters are said to be one of the key issues in engineering change management (Masmoudi et al. 2017b), for example, because those dependencies establish relationships between components (Tang et al. 2016). Change propagates among parameters that are derived from one another by calculation, or that are linked by constraints (Xie and Ma 2016). Design parameters may also have a direct or indirect impact on metrics describing a design's performance (Ollinger and Stahovich 2004) and its cost (Rebentisch et al. 2017).

3.2.5 Change propagation may involve geometry

Change may propagate among parts that are adjacent or that share packaging space (Stocker et al. 2017). Change can also propagate if geometry directly involved in the mating between parts in an assembly is modified (Eltaief et al. 2017), e.g. if topology faces of a part that are constrained to faces on other parts are changed (Yin et al. 2017b, 2016; Chen et al. 2020). Early in the design process, before detailed part features have been created, changes to datum geometry such as axes, planes, and envelopes in skeleton models can also cause propagation (Hwang et al. 2009). Apart from mating, other constraints such as parallelism and concentricity can cause geometric change to propagate (Masmoudi et al. 2017b, a). Geometry is closely related to design information in many other domains discussed in this section, leading to further propagation possibilities (Ma et al. 2008).

3.2.6 Change propagation may involve design representations

A design is defined by its parameters and geometry but these are represented in artefacts such as documents, CAD models and Bill of Materials (BOM) items. Such representations may be interdependent because they describe different aspects of the same design, perhaps on different levels of description or in different file formats (Wynn et al. 2011). Dependencies among design representations also occur due to the hierarchical structure of design information. For example, if a BOM item is changed, others up and down the hierarchy can also potentially change (Ho and Li 1997). As a design evolves through changes, the interdependent representations need to be updated to ensure consistency, which is a form of change propagation (Leng et al. 2016; Xue et al. 2006).

3.2.7 Change propagation may involve design behaviours or performance parameters

Performance parameters are related to product requirements (Yu et al. 2017) in that they determine whether a product performs to the required levels (Ouertani and Grebici 2011; Koh et al. 2012; Koh 2017). A design change may propagate to affect design performance parameters if the design is to meet different requirements (Chen et al. 2007; Mirdamadi et al. 2018; Ollinger and Stahovich 2004; Zhang et al. 2017). Respecification of performance parameters has also been attributed to deficiencies in design behaviour (Li and Chen 2007, 2010). Since there is a many-to-many relationship between design parameters and performance parameters, when changing one design parameter others might also need to be adjusted to avoid deteriorating performance (Brahma and Wynn 2021).

3.2.8 Change propagation may involve design tasks

Change propagation can also be viewed in terms of the (re) design tasks undertaken. When a change is made, some previously completed tasks downstream in the design process may need to be revisited. Lian et al. (2017) suggest that the tasks that might require rework correspond to the components involved in the change. On a more detailed level, changes to a task's input can propagate to cause changes to its output (Li et al. 2012). These inputs and outputs can involve changes to design parameters (Ahmad et al. 2013) or models of the design, such as CAD files (Wynn et al. 2014). Dependencies among tasks, through which change can propagate, can occur at multiple levels of decomposition and can be of different types, e.g. reflecting sequential, overlapping, and concurrent execution of those tasks (Ouertani and Grebici 2011).

3.2.9 Change propagation may involve design process participants

Different design process participants are responsible for different design parameters and so, when a parameter is changed, the resulting propagation can involve several team members who need to exchange information and negotiate a solution (Ouertani and Grebici 2011; Kattner et al. 2018). In addition, the social context of an engineer's work, including their connections within the organisation, influences the propagation of changes they are involved with (Pasqual and de Weck 2012).

3.2.10 Change propagation may involve manufacturing systems and impact other lifecycle phases

Design changes to components propagate to cause changes in manufacturing systems and processes (Fei et al. 2011). For instance, change to a component design may impact its manufacturability (Chen et al. 2017) and will often propagate to change the manufacturing operations (Tseng et al. 2008). Conversely, change may propagate from manufacturing to the component design, e.g. the design might need to change because a certain material is no longer available (Ahmad et al. 2013), or to enable manufacturing system improvements such as better weld accessibility (Isaksson et al. 2021). Similarly, to make production requirements feasible, it may be essential to adapt process parameters (Hoang et al. 2017b, a), which are in turn dependent on other design parameters. Changes can also propagate within manufacturing systems without affecting the design (Plehn et al. 2016).

Design changes may also have significant disruptive effects on the supply chain (Khan et al. 2008). Lin and Zhou (2011) for instance categorise the risk to supply chain arising from design change risk into two categories: Internal risks, in which design change may affect R&D, production and planning; and external risks, in which supply and delivery may be affected by design changes. For original equipment manufacturers with a distributed supply chain, changes in design may also disrupt inventory planning and management (Shivankar and Deivanathan 2021). Although these examples focus on manufacturing and supply chain, design change can propagate to affect other lifecycle phases as well, since all are impacted by (and should influence) design decisions.

3.3 Influences on change propagation

Section 3.2 has established that change has potential to propagate through various information domains, according to dependencies within and across those domains. While the dependencies create possibilities for propagation, whether or not propagation actually occurs through a specific dependency in a specific situation is subject to a variety of influencing factors. These are summarised in the top-centre box of Fig. 1 and discussed in Sects. 3.3.1–3.3.7.

3.3.1 The properties of connections among design elements and the type of change influence how change may propagate

The way in which two elements are connected is very commonly assumed to influence whether change propagates between them or is absorbed. This has been conceptualised in different ways. For instance, different dependencies may have different strengths or characteristics (Rutka et al. 2006; Lemmens et al. 2007). To provide an example, if the connection between two components of a design is spatial in nature, a change may propagate differently than if the part connection involved energy, material and/or signal (Hamraz et al. 2013d). As well as differences in the types of connection, changes themselves have different natures (Rutka et al. 2006). There is a relationship between the type of a change, the properties of a dependency, and whether or not the change propagates. For instance if a change only impacts a signal emitted by a part, it may propagate through signal connections but not directly through spatial connections. In addition, recognising the relationship between change type and propagation, Mehta et al. (2012) and Chen et al. (2017) argue that similar types of change propagate in similar ways.

3.3.2 Different magnitude/extent of change may propagate differently

A design change can be of different extent or magnitude, for example, a dimension may change by a small amount or by a much larger amount. Changes of different magnitudes can have different impacts (Rutka et al. 2006; Lemmens et al. 2007). Changes up to a certain magnitude may be tolerable and be absorbed, while changes above that magnitude may cause propagation (Hamraz et al. 2013d; Brahma and Wynn 2021). If propagation occurs, the magnitude of the knock-on effects may be influenced by the magnitude of the initiating change (Wynn et al. 2014).

3.3.3 Elements may have different sensitivities to change

As already discussed, tasks in the (re)design process can propagate change from their inputs to their outputs. Whether or not this occurs is influenced by how sensitive the task is to the modified input information (Wynn et al. 2014). The effort and time required to rework a task is also dependent on task sensitivity to change (Wynn et al. 2014), as well as whether the task had been started or not when the change is initiated (Chua and Hossain 2012). If the change does propagate, its impact on immediately-downstream tasks depends on the nature of the dependency between tasks (Chua and Hossain 2012; Ouertani and Grebici 2011). Therefore, sensitivity of a task due to change depends on where in the design cycle the change occurs (Li et al. 2015). Applying similar ideas to propagation within a designed system, some variables in a system may be more flexible than others and, therefore capable of handling external uncertainties to varying degrees (Wei et al. 2016).

3.3.4 Change propagation may be absorbed by design margins

The way a change propagates or gets absorbed depends on margins in a designed system, which can buffer such changes (Long and Ferguson 2019; Li et al. 2021a; Brahma and Wynn 2021). The way designers allocate margin, therefore, has the capability to influence change propagation (Eckert et al. 2004). Excessive margins, however, can also have undesirable effects such as cost and schedule overruns (Shabi et al. 2021). A design can have elements which are known change multipliers. Change may propagate readily if margins of such change multipliers get consumed (Eckert et al. 2004). Closely related, modular products are more easily adaptable due to the system of interfaces (Baldwin and Clark 2000), which have built-in margins allowing change to be absorbed within a subsystem (as long as it does not require interface change).

3.3.5 Change propagation can be influenced by design freeze

Design freezes are implemented on components or subsystems as the design process moves forward. As component designs are frozen, the possible propagation paths change (Eger et al. 2005; Keller et al. 2005) and in particular, changes that would otherwise involve those components must be handled by redesigning others (Ahmad et al. 2013).

It has been suggested that design freeze could be used as a way of controlling change propagation by redirecting the change in a desirable way (Hamraz et al. 2013c). For example, designers block changes to certain components where it is desirable to preserve their configuration (Krishnamurthy and Law 1997). Selective freezing of components that are expensive to change, or are standardised, can ensure those components are not impacted when a change propagates (Ullah et al. 2017b). Overall, design freeze limits the number of candidates for change absorption in later stages of product development (Lee and Hong 2015).

3.3.6 The design team may choose how to implement change propagation

As suggested in several of the previous subsections, change propagation does not only depend on the characteristics of the design, the design context and the change itself, but also on designer decisions. A product structure typically allows a multitude of redesign options.Therefore, a designer may choose to implement changes in different ways (Ariyo et al. 2009; Yang and Duan 2012).

Different ways to implement a change may result in different propagation routes (Koh et al. 2012; Yang and Duan 2012). Some of those routes may turn out to be more costly than others, and therefore should be avoided (Ahmadinejad and Afshar 2014). At the same time, designers may choose to make additional localised changes to negate propagation effects (Ollinger and Stahovich 2004).

3.3.7 Design progress influences how changes may propagate

Change propagates through dependencies, but the structure of dependencies changes during the design process, as do the aforementioned influences on whether or not a change will propagate through a particular dependency (Jeong et al. 2019). For example, as more design issues are progressively taken into account, a denser structure of dependencies is generated in the design and changes become more likely to propagate. Margin may also be reduced over time as a design is further optimised, causing changes to propagate more easily (Long and Ferguson 2020). Parts may become more sensitive to changes over time as they are further detailed and optimised. The results of design refinement tasks are more likely to be impacted by changes to the task input than tasks earlier in the design process, because the latter are undertaken in expectation of uncertainty (Li et al. 2021a). As time progresses, parts of a design may already be in manufacturing or may be frozen, meaning that they are excluded from potential propagation while remaining decisions are more likely to be impacted instead (Leng et al. 2016). For all these reasons, it is desirable to avoid changes later in the design process, when the corresponding design rework is likely to be greater.

4 Key concepts relating to methods for change propagation analysis

Building on the context and theory of change propagation analysis as discussed in Sect. 3, researchers have developed computable models to support change propagation analysis. This section moves on to discuss the key principles of such models. It is organised into four subsections as depicted in the bottom row of Fig. 1:

- Sect. 4.1 presents techniques to *represent* input information that is required to perform CPA.
- Sect. 4.2 discusses approaches to *populate* those representations with data to enable CPA in a specific design context.
- Sect. 4.3 discusses techniques to *analyse* those representations to assess change propagation.
- Sect. 4.4 discusses approaches to *visualise* the results of change propagation analysis.

4.1 Representation of CPA input

To recap, change propagation analysis (CPA) is based on the assumption that change propagates through relationships between discrete elements in the design context. The types of element and relationship that are used for CPA input strongly influence the design situations in which a particular approach can be used. For example, CPA approaches based on CAD geometry are applicable only later in the design process once that geometry has been created, while those based on dependencies among subsystems can be used earlier, as soon as the product architecture is firmed up.

The next subsections discuss approaches that have been used to represent elements and relationships as input to CPA approaches. The approaches are summarised in the top-left cell of the bottom row of Fig. 1.

4.1.1 CPA model input can be represented using a Design Structure Matrix

The first category of input representation to be discussed concerns use of a Design Structure Matrix (DSM) to represent connections between elements of a single domain, through which change can propagate. Clarkson et al. (2004) and Jarratt et al. (2004), for example, use a component/subsystem DSM as shown in Fig. 3 to represent the input to their change propagation method (CPM). Much work that builds on CPM also uses this approach (e.g. Jarratt et al. 2004; Keller et al. 2005; Ariyo et al. 2007; Hamraz et al. 2013a, d; Maier et al. 2014; Stocker et al. 2017). A variety of schemes have been used to characterise each propagation dependency in an input DSM. For example, Clarkson et al. (2004) supplement each dependency with likelihood and impact of change propagation through that dependency, Ma et al. (2003) indicate whether each dependency represents spatial, material, energy and/or information constraints, while Rutka et al. (2006) indicate types and levels of change that can propagate through each dependency. These are just a few examples; many other variations on DSMs used as input to CPA models can be found in the literature. Advantages of using a DSM as a CPA model input include that a DSM allows a dense structure of dependencies to be easily modelled and visualised; a DSM can be easily constructed in commonly-available spreadsheet software; and that a lot of information can be presented in a small space while remaining readable. On the other hand, (like many visualisations) DSMs can become more difficult to read as the number of elements increases. This can be observed by comparing Figs. 3 and 9.

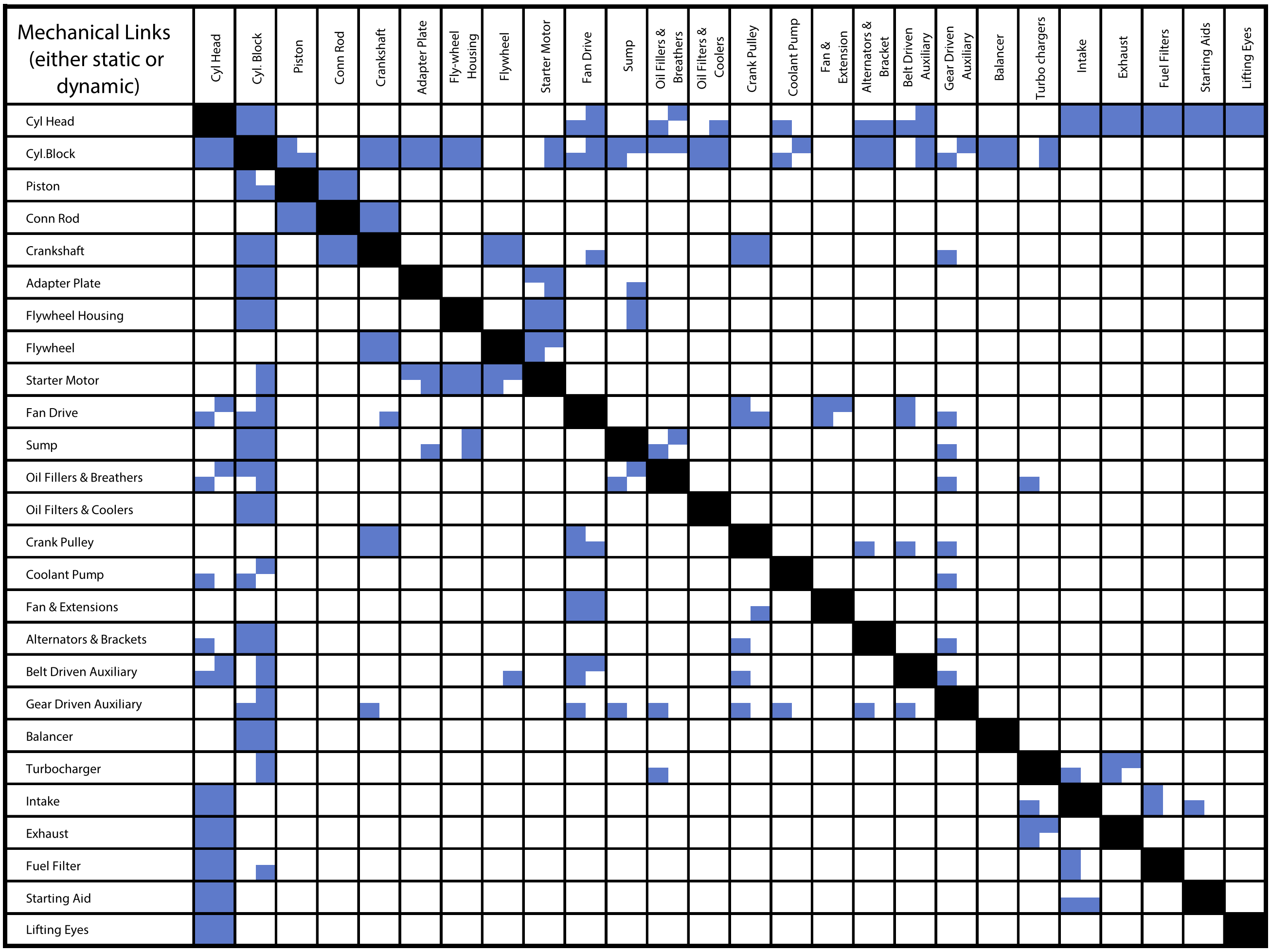


Fig. 3 DSM of a diesel engine used for CPA model input, showing mechanical linkages between subsystems from the viewpoints of four engineers. The position of the coloured boxes within the cells refers to a particular engineer's marks. Reproduced from Jarratt (2004) with permission of the author

4.1.2 CPA model input can be represented using cross-domain matrices

Expanding on the DSM concept, other researchers use incidence matrices to represent dependencies across multiple information domains for CPA model input.

Some use an essentially DSM-based representation that is expanded to include data in multiple domains. For example, Bracken et al. (2018) introduce a C+C DSM which represents both components and the constraints on their design, along with the connections among these elements. Others have used multiple DSMs as input to their CPA methods. For example, Tang et al. (2010) use three DSMs to represent product, process and organisation, respectively.

Other CPA researchers explicitly define non-square incidence matrices to capture propagation dependencies across different domains. For instance, Chen et al. (2007) and Tang et al. (2016) use a Design Dependency Matrix (DDM), while Rebentisch et al. (2017) use a Design Mapping Matrix (DMM). Both are mapping tables that represent relationships between two domains. As with DSM-based representations, the relationships can be characterised with numbers or other indicators (e.g. Hoang et al. 2017b, a).

A more comprehensive matrix system called Multiple-Domain Matrix (MDM) combines square DSMs and non-square mapping matrices to represent dependencies within and across domains (Lindemann et al. 2009). Like DSMs, MDMs also frequently appear in CPA models (e.g. Fei et al. 2011; Hamraz et al. 2012; Zou and Yang 2018). For example, Koh et al. (2012) represent product components, options and requirements in an MDM (Fig. 4). Flanagan et al. (2003) use matrices that map components, functions and features, while Siddharth and Sarkar (2017) map design parameters onto manufacturing parameters.

In comparison to single-domain DSMs discussed in the previous subsection, using matrices that combine domains for CPA input allows for more finely grained and cross-domain analysis. This may help to avoid overlooking propagation dependencies that occur where design decisions must account for multiple domains. Such approaches typically require a greater amount of data that a single-domain DSM to model the same system. Both in single-domain DSMs and multi-domain DSMs, the data requirement can be managed by appropriate choice of granularity level when modelling (see also Maier et al. 2017). Granularity of an input model has a direct impact on the level of resolution in CPA results.

4.1.3 CPA model input can be represented using a network diagram

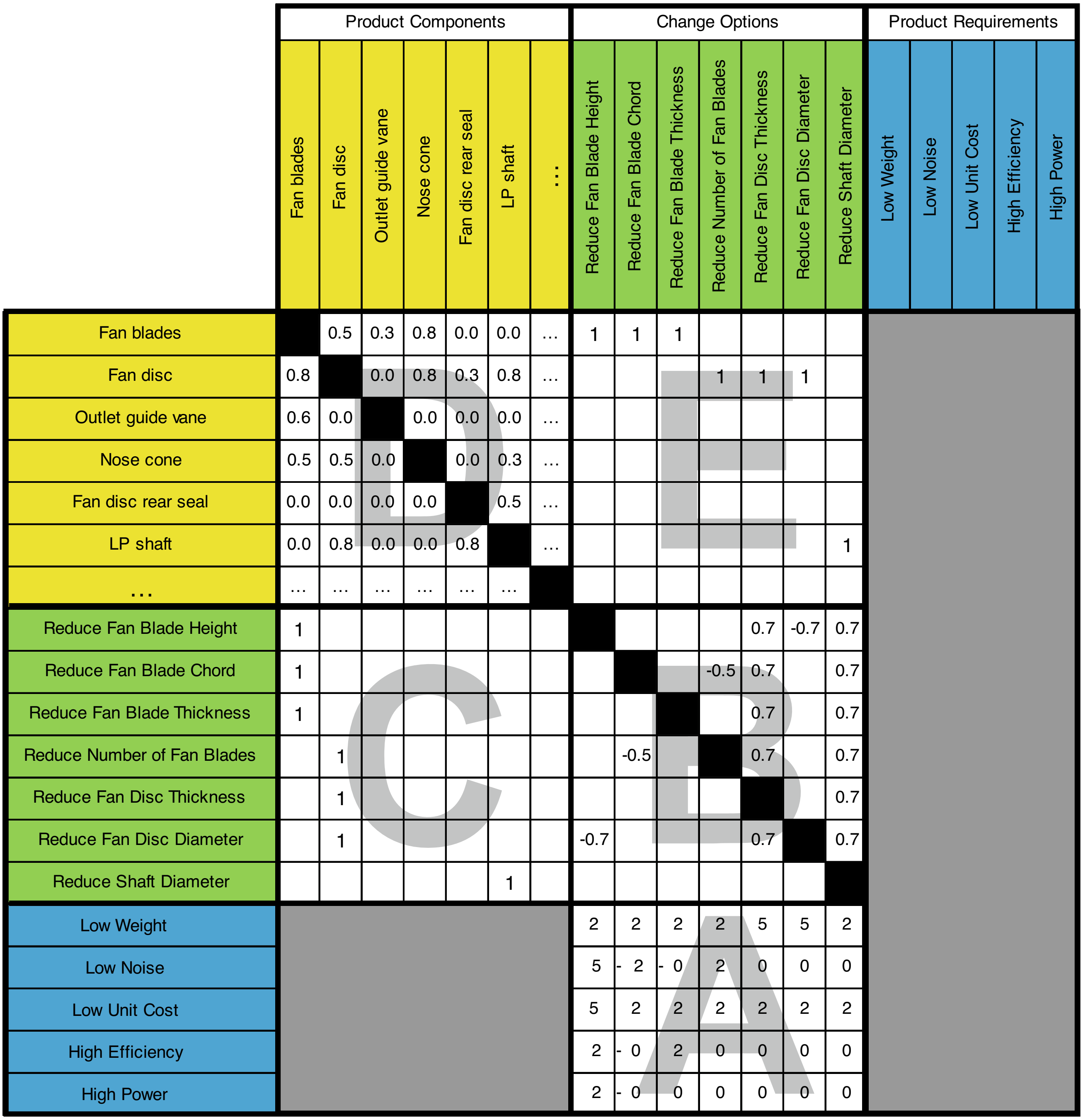
Another approach to specifying dependencies for CPA is to represent them as a network diagram. For example, workflow diagrams have been used to represent propagation dependencies between tasks for CPA (e.g. Wynn et al. 2014), as shown for example in Fig. 5. Ma et al. (2016), Ma et al. (2017) and Jeong et al. (2019) use network diagrams to represent relationships and constraints between design parameters. Others use network diagrams to specify dependencies across multiple domains (e.g. Ahmad et al. 2013; Lee et al. 2010; Pasqual and de Weck 2012). Conrad et al. (2007) use a manually laid out Characteristics–Properties Modelling/Property-Driven Development (CPM/PDD) network diagram as the basis of their change risk assessment procedure. Network diagrams can also be created automatically using graph layout algorithms, which is helpful to visualise the complex network structures in CPA input data extracted from, e.g. a DSM and a database.

Overall, the use of network diagrams as CPA model input has the advantage of being familiar to practitioners. Such diagrams are also easy to read for simple cases and are especially suitable if there is an overarching direction of propagation dependencies to be modelled. However, they can become difficult to comprehend as the number of elements and density of interactions increase, and require specialised tools if computable data is to be extracted automatically to enable CPA.

4.1.4 CPA model input can be represented using databases

Whereas matrix and network representations present essentially graphical and holistic views of propagation dependencies, other authors have used databases (or other systems involving records of individual elements and dependencies) to represent the input information for CPA. For instance, Kocar and Akgunduz (2010) proposed a database to store various aspects of product related data relevant to CPA. Similarly, Leng et al. (2016) developed a CPA approach based on manufacturing bill of materials (MBOM) and engineering bill of materials (EBOM) information in a database. Xue et al. (2006) developed an evolutionary design database for CPA, which captures geometric evolution alongside other descriptions reflecting different stages of design. In their approach different stages of design are modelled as a collection of worlds. Differences between worlds reflect change propagation between the stages. Ma et al. (2017) used an ontology web language (OWL) database as input for CPA, thereby organising design properties into a hierarchy of concepts. Other authors use databases of design information as data sources to populate a matrix or network diagram which is then used for CPA. Approaches of this type are discussed in Sect. 4.2.

In comparison to matrix and network-based approaches, database approaches allow richer information to be represented. This expands the possibilities to support CPA, for instance enabling analysis of historical change patterns.



	Product Components							Change Options							Product Requirements				
	Fan blades	Fan disc	Outlet guide vane	Nose cone	Fan disc rear seal	LP shaft	…	Reduce Fan Blade Height	Reduce Fan Blade Chord	Reduce Fan Blade Thickness	Reduce Number of Fan Blades	Reduce Fan Disc Thickness	Reduce Fan Disc Diameter	Reduce Shaft Diameter	Low Weight	Low Noise	Low Unit Cost	High Efficiency	High Power
Fan blades	■	0.5	0.3	0.8	0.0	0.0	…	1	1	1									
Fan disc	0.8	■	0.0	0.8	0.3	0.8	…				1	1	1						
Outlet guide vane	0.6	0.0	■	0.0	0.0	0.0	…												
Nose cone	0.5	0.5	0.0	■	0.0	0.3	…												
Fan disc rear seal	0.0	0.0	0.0	0.0	■	0.5	…												
LP shaft	0.0	0.8	0.0	0.0	0.8	■	…							1					
…	…	…	…	…	…	…	■												
Reduce Fan Blade Height	1							■				0.7	-0.7	0.7					
Reduce Fan Blade Chord	1								■		-0.5	0.7		0.7					
Reduce Fan Blade Thickness	1									■		0.7		0.7					
Reduce Number of Fan Blades		1							-0.5		■	0.7		0.7					
Reduce Fan Disc Thickness		1										■		0.7					
Reduce Fan Disc Diameter		1						-0.7				0.7	■	0.7					
Reduce Shaft Diameter						1								■					
Low Weight								2	2	2	2	5	5	2					
Low Noise								5	- 2	- 0	2	0	0	0					
Low Unit Cost								5	2	2	2	2	2	2					
High Efficiency								2	- 0	2	0	0	0	0					
High Power								2	- 0	0	0	0	0	0					

Fig. 4 Multiple Domain Matrix used by Koh et al. (2012) as input for change propagation analysis. Reproduced with the permission of Springer Nature BV

On the other hand, the more complex information is not as straightforward to visualise, verify and communicate.

4.1.5 CPA model input can be represented using geometry descriptions

Some researchers use geometric models of the design as input for CPA. Such representations can use different levels of resolution. For example, Chen et al. (2017) use actual geometric definitions of parts, including their relationships. Other researchers use simplified geometric information as CPA input data, such as the matings between specific features or surfaces (e.g. Yin et al. 2016, 2017b). Ou-Yang and Chang (1999) combine this approach with information about the assembly approach and constraints on geometric definition parameters. Eltaief et al. (2017) use geometric

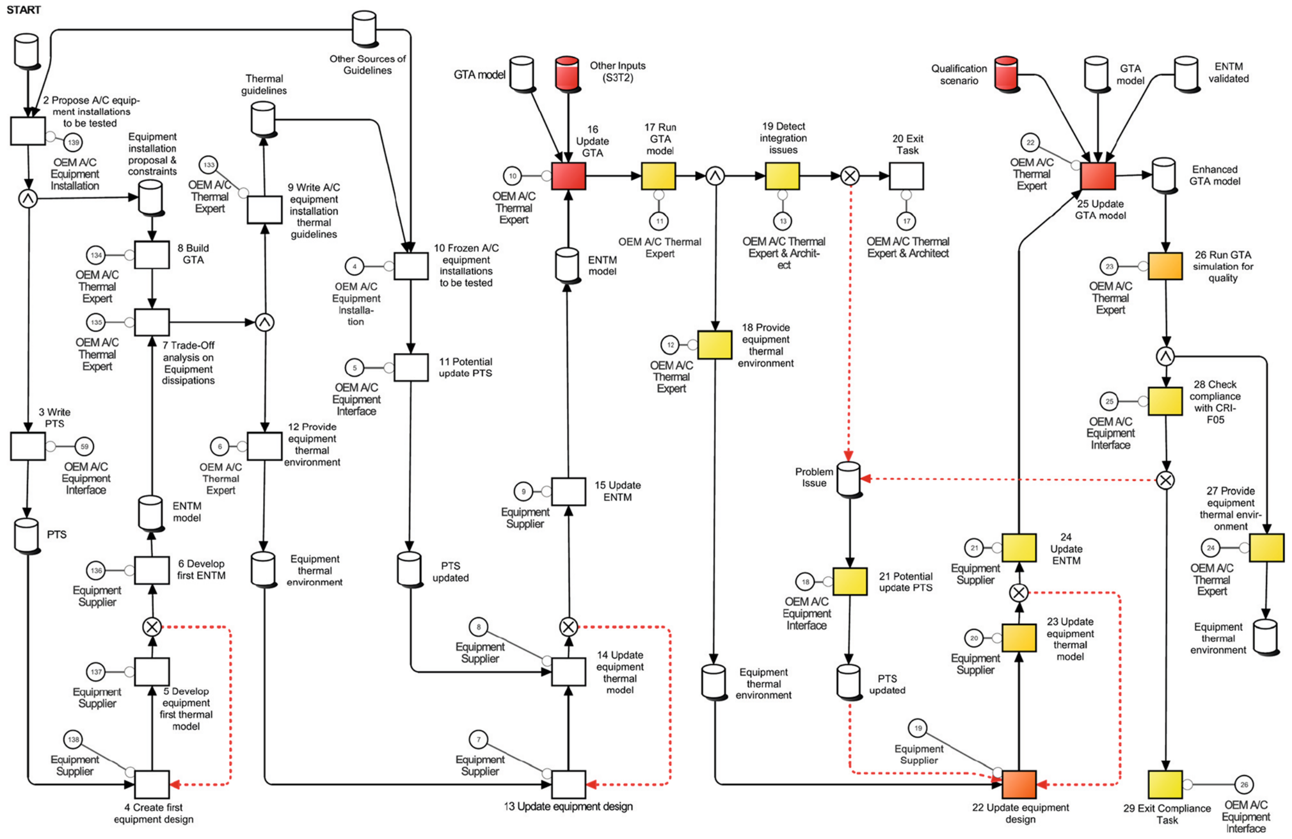


Fig. 5 A graphical workflow model used as input to a change propagation analysis. Reproduced from Wynn et al. (2014) with permission of ASME

references relating to six types of feature including planar faces and cylindrical faces, while Hwang et al. (2009) develop a CPA approach based on geometric skeleton information such as datum elements and part envelopes. You and Chao (2009) use information from two different CAD sources, namely mechanical and industrial designs.

Overall, the main advantage of using geometric design representations as input for CPA is that they allow analysis of spatial propagation on a level of detail and accuracy that is not possible from the abstracted representations discussed in previous subsections. On the other hand, they are complex to develop (or extract from CAD models) and may be complex to process for propagation analysis. They are also mainly focused on a snapshot in time of the design, so due to their high level of detail may need to be regularly updated so that CPA remains accurate. Other challenges with this approach include handling designs with complex motions and configurations, and obtaining the necessary information if CPA is to be used in early design stages before parts are geometrically defined.

4.1.6 CPA model input can be represented using a diagram mimicking a design's layout

Another representation of geometric information used as input for CPA is a diagram that approximates the physical layout of a design. For example, Albers et al. (2011) propose a diagram representation that focuses on the functional interactions between parts (Fig. 6). In this representation, lines joining parts indicate a physical contact surface where the parts must work together to realise a function. Albers et al. (2011) discuss how the contact surfaces can drive change propagation between the pair of involved parts. In another approach, Stocker et al. (2017) propose a representation that captures propagation linkages that occur where components are adjacently positioned or share packaging space (Fig. 7). These approaches allow CPA to account for geometric considerations on a higher level of abstraction and without need for the detailed geometric data mentioned in the previous subsection. However, it is not clear how well they would scale to more complex geometry than the examples shown.

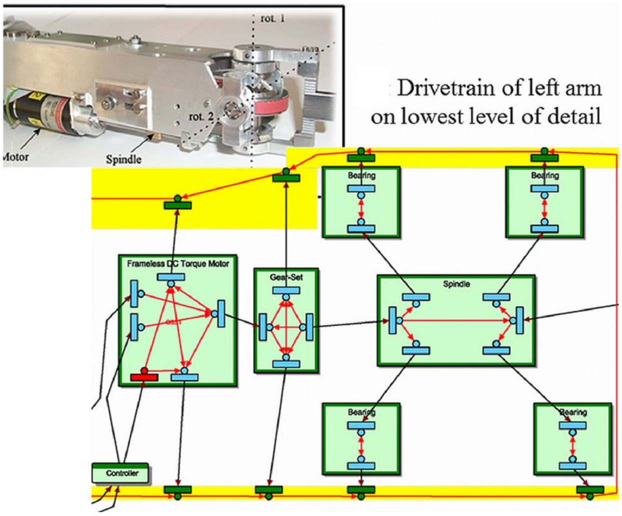


Fig. 6 CONTACT AND CHANNEL APPROACH to diagramming the surfaces where component pairs interact to realise a function to identify possible propagation dependencies. Reproduced from Albers et al. (2011) with permission of ASME

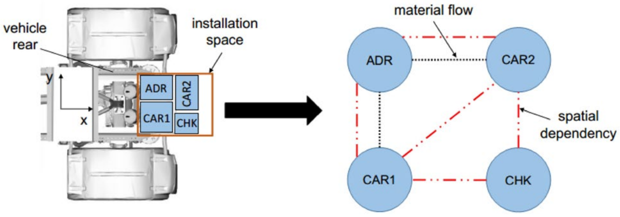


Fig. 7 Diagramming shared package space as an input to determine change propagation dependencies. Reproduced from Stocker et al. (2017)

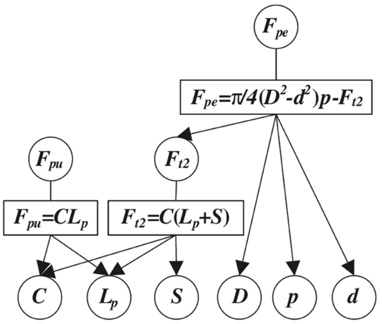


Fig. 8 Decomposition of parameters into three types in Yang and Duan (2012)'s parameter linkage-based method. The top-most parameter is the target parameter. The ones at the bottom are direct parameters, and the ones linking the two are transition parameters. Reproduced with the permission of Springer Nature BV

4.1.7 CPA model input can be represented using hierarchical decomposition

One of the challenges of handling the input information for CPA is that the numbers of elements and relationships can increase rapidly with the complexity of the design under consideration. Especially in the case of detailed elements such as parameters, huge numbers of elements and connections would need to be considered to represent a design of any scale (Siddharth and Sarkar 2017). This is problematic in terms of data acquisition and visualisation, and increases the time required for propagation analysis itself.

Different approaches have been used to address this problem by hierarchical decomposition of CPA input data. The first is to decompose high-level elements into different types of elements at a more granular level of definition. For example, as shown in Fig. 8, Yang and Duan (2012) decompose parameters into direct parameters, which can be adjusted by designers, and transition parameters, which define the link between direct and target parameters. Other approaches (discussed in previous subsections) are hierarchical in the sense that they decompose parts into surfaces and/or features (e.g. Ou-Yang and Chang 1999; Flanagan et al. 2003), and so on. Another approach is to decompose the same type of element into multiple hierarchical levels. For instance Yang and Duan (2012) argue that hierarchical decomposition of parameters can support the development of propagation relationships among them, while Ariyo et al. (2007) discuss the clustering of components into subsystems at multiple levels to acquire and manage CPA input data for complex products.

Hierarchical input data for CPA can be visualised and manipulated in various ways, such as using a hierarchical DSM or hierarchical network diagram. To assist with the large volumes of data typically involved, some approaches allow users to interactively open and close elements of a model to focus on aspects of interest. For instance, this approach is used by Albers et al. (2011), as depicted in Fig. 6 in which one of the depicted components is closed, obscuring the detail within it.

4.2 Populating models of change propagation

The next category of our organising framework concerns how the information required for CPA is generated, collected or elicited. Approaches discussed in the literature are shown in the bottom-leftmost box of Fig. 1 and elaborated in the next subsections.

4.2.1 Data required for CPA can be generated by analysis of a design or concept

One method for populating models is to analyse an existing design by decomposition and inspection. In some cases a decomposition of the design into suitable elements for CPA might already be available, while in other situation a decomposition must be developed from specifically for this purpose (Hamraz et al. 2012).

Some researchers decompose designs based on systematic processes such as creating patterns or clusters in matrices (Chen et al. 2007; Li and Chen 2007, 2010, 2014), while some use systematic decomposition methods such as functional decomposition (Raffaeli et al. 2007; Rios-Zapata et al. 2017; Xue et al. 2006; Damak et al. 2021), function-structure (Ma et al. 2008; Albers et al. 2011; Li et al. 2017), function-behaviour-structure (Koh et al. 2012), function-parameter (Oizumi and Aoyama 2020) and spatial breakdown by the designer or a team of designers (Yu et al. 2017).

A second approach to data generation by analysis is to inspect the existing design followed by systematically answering specific 'if...then'-type questions to identify items potentially affected by changes (Conrad et al. 2007). Methods of extracting CPA data by decomposition or by inspection have been critiqued for producing subjective outcomes depending on how the design is decomposed (Ahmad et al. 2013). Moreover, the thoroughness of the method and of its execution greatly influence the quality of data obtained.

A third approach is to analyse a design to elicit parametric relationships. The analyst may, for example, first identify parameters related to the input specifications and required performance parameters and then trace the relationships between them by looking at engineering calculations (Brahma and Wynn 2020; Yang and Duan 2012; Ou-Yang and Chang 1999; Ma et al. 2016, 2017). While eliciting parametric relationships for CPA may arguably be more objective and repeatable than decomposition-based methods in more abstract domains, it is likely to be challenging for complex products where thousands of parameters may be involved, as well as situations in which the parametric relationships are not fully known at the time CPA is required. These methods may also be difficult to apply in situations where computational methods such as finite element analysis or computational fluid dynamics are used during design. Parametric relationships in such situations might be generated based on approximations such as response surfaces or surrogate models, but this would also be difficult in multivariate scenarios, which are common.

4.2.2 Data required for CPA can be generated by workshops and/or interviews to elicit expert judgement

Other researchers populate their models by eliciting expert judgement about potential change propagation, mainly based on past experience of changes. For instance, Clarkson et al. (2004) used workshops with designers and experts to decompose a design and establish potential propagation relationships between components. They supplemented this with interviews with experienced design managers in order to estimate propagation probabilities between each pair of components.

Some approaches are based on asking experts to assign qualitative ratings. For example, Cheng and Chu (2012) use the rating systems of Martin and Ishii (2002) and Pimmler and Eppinger (1994), in which experts rate the sensitivity of a part to change. The rating system may help maintain consistency of assessments. Similarly, Kim et al. (2013) develop a method in which designers are asked to fill a checklist with their assessments of risk and impact on a set of predefined topics. This approach may help to ensure important points are not missed. Cohen et al. (2000) employ a series of specific questions for the domain experts to answer to systematically identify propagation linkages.

Where probability distributions are required for a CPA approach, experts may be asked to estimate parameters for those distributions, based mainly on past trends of change propagation (e.g. Chua and Hossain 2012; Raffaeli et al. 2013; Wynn et al. 2014).

Researchers have pointed out the limitations of expert-based elicitation methods, mainly stemming from the complexity associated with most designs and the subjectivity of the resulting data. For example, Clarkson et al. (2004) write that due to the collaborative nature of design, no process participant knows the entire design in detail.This makes knowledge elicitation difficult and time-consuming (Rutka et al. 2006). Cohen et al. (2000) state that multiple domain experts must be interviewed to accurately extract all the necessary information.

4.2.3 Data required for CPA can be generated by analysis of historical change data

Data for populating CPA models may be available in the form of historical documentation in an organisation, reducing or eliminating the need to elicit knowledge from expert designers or to perform a design decomposition. Lee and Hong (2018) for example, discuss a method to extract data required for CPA from a design history database. They extract a change log from the database to an appropriate level of granularity, on which they apply learning algorithms to create a dependency network which is the basis for their CPA approach. Other researchers have also applied data-mining algorithms to extract data for CPA (Kocar and Akgunduz 2010). Mehta et al. (2013), for example, formulate the problem of identifying important attributes for comparing changes against historical change data as a multi-objective optimisation problem, and apply ant-colony optimisation to solve it. In their approach, the important attributes set informs prediction of future changes.

Pasqual and de Weck (2012) point out that the method of data extraction from historical change records to support CPA will depend on the source and the type of data being extracted. For example, while data pertaining to relationships between design parameters may be extracted by analysing design records, data pertaining to the social aspects could be extracted by examining staffing records, meeting minutes and so on.

4.2.4 Data required for CPA can be generated by extract from PLM/PDM or CAD

Some researchers extract data for CPA from product lifecycle management/product data management (PLM/PDM) systems or from CAD, requiring little or no additional input. These data are developed during the design process and, therefore, are easily accessible, at least in principle. For instance, Yin et al. (2016) develop an algorithm that acquires constraint information between topology faces from CAD models, and uses it to create a relationship matrix for CPA. Similar feature-constraint-based extraction approaches were developed by Yin et al. (2017b), Eltaief et al. (2017) and Ou-Yang and Chang (1999). (Masmoudi et al. 2017b, a) discuss how dependencies between dimensions can be extracted by adjusting those dimensions in CAD, observing how geometric constraints in the CAD model cause other dimensions to change as well. Chen et al. (2017) propose a method in which changed features are detected by comparing CAD files. The identified changed features are then compared to past changes to support CPA.

Apart from being restricted to the geometrical domain, the results of such analysis are dependent on how the design is built up in CAD, including how (and how comprehensively) constraints are modelled. A practical consideration which may hinder the development of CAD-based approaches is the need to handle a variety of CAD data types and formats (see, e.g. You and Chao 2009; Hwang et al. 2009).

4.3 Techniques to analyse change propagation

Having discussed the different approaches for representing and visualising connectivity data in CPA literature, and approaches for generating or eliciting that data for a specific design context, we now move on to the approaches researchers have used to analyse change propagation using that data. In our framework, the key concepts in this category are summarised in the middle box of the bottom row of Fig. 1. They are discussed in the next subsections.

4.3.1 CP can be analysed by applying probabilistic methods to a network of dependencies

Approaches in this category involve first, generating a network of dependencies through which change can propagate, and second, applying probabilistic techniques to assess how change might propagate within that static network.

Some approaches of this type create static propagation trees to capture all possible routes for propagation from a certain initiating component, up to a certain number of steps. The tree is then processed using statistical operations to determine the likelihood of change propagating from that initiating component (the root of the tree) to any other component (at the leaves of the tree) considering the propagation probabilities of each dependency and that multiple paths are possible between any two components. The first and most established method of this type is the CPM of Clarkson et al. (2004). The technique is often enhanced by qualitative improvements on the impact-likelihood dependencies. Levels of impact and likelihood for example may be influenced by the type and degree of change (Rutka et al. 2006) which may in turn be influenced by when the change is initiated in the overall design process (Chua and Hossain 2012). Consideration may also be given to the interfaces between components in a propagation path, since interface characteristics such as design margins may influence the probability of a change propagating (Hamraz et al. 2013d; Ma et al. 2016). Reddi and Moon (2009) model dependencies in terms of the type of change and the likelihood that it would propagate, proposing an algorithm to iterate through the model to identify all propagation paths.

Another group of methods in this category use Bayesian Networks to predict change propagation in a network of propagation dependencies (Lee and Hong 2017; Mirdamadi et al. 2018; Chen et al. 2017; Hu and Cardin 2015; Yeasin et al. 2019; Diallo and Zolghadri 2018). One advantage of this approach is that it provides for inference from historical empirical data change records while also taking account of expert opinion. The methods discussed in the previous paragraph, in comparison, are static, and an element can only be in a “change” or “no change” state for a particular propagation path (Lee and Hong 2017). But Bayesian network analysis requires more comprehensive statistical information in the input model.

Overall, one advantage of the techniques discussed in this subsection is their accounting for uncertainty (expressed as probabilities) in the CPA input information. This is advantageous for situations modelled at a high level of abstraction or where the details of dependencies are not available. At the same time, the probabilistic outputs mean they can only indicate ranges or risks of outcomes, and cannot predict the specific outcomes of specific changes.

4.3.2 CP can be analysed by Monte-Carlo simulation of the propagation process

The second group of methods, instead of generating a static network which is then processed, apply Monte-Carlo

Simulation (MCS) to simulate individual changes as they propagate step-by-step.

For example, Wynn et al. (2014) apply MCS on design workflow models, that include logic gates, deliverables and task sensitivities to change, to propagate changes through those workflows and estimate the effort and duration of a change process. Li et al. (2012); Li and Zhao (2014); Li et al. (2017) apply a MCS approach to trace propagation paths and, in cases where multiple ways to resolve a propagation could be decided, to recommend the route that is likely to be most efficient. Random search algorithms to identify the best propagation routes from the range of possibilities implied in CPA input data are used by Plehn et al. (2016); Rebentisch et al. (2017). Lian et al. (2017) approach this problem using the Cuckoo search algorithm.

To summarise, approaches based on MCS can cope with complex propagation logic and can evaluate different scenarios for optimising change decisions. However, the computed optimal change route may be sensitive to probabilistic assumptions in the input data (often based on practitioner estimates), and it is not clear how to verify that the possible propagation routes generated by simulation and their estimated costs are realistic. In addition, such algorithms can be computationally expensive for larger models, since the number of possible paths increases rapidly with the scale and connection density of a modelled situation.

4.3.3 CP can be analysed by matrix operations and calculations over matrix cells

This subsection discusses techniques in which operations on whole matrices are used in propagation analysis. One common approach is to multiply a DSM by itself to combine direct and indirect propagation routes between each pair of elements. For instance, Schuh et al. (2017) primarily use matrix multiplications in their approach to calculate the effects of degrees of freedom on a changeable system. Matrix multiplication also commonly appears in other CPA approaches such as Tang et al. (2016); Yin et al. (2016, 2017b); Luedeke et al. (2017). Other matrix operations such as summation are used by Yin et al. (2017a), while Cohen et al. (2000) develops a quite intricate approach based on multiplication of matrices and vectors. Methods involving multiplication of composite matrices such as MDMs to obtain indirect propagation paths have also been proposed (Fei et al. 2011; Wei et al. 2016; Rebentisch et al. 2017). Hamraz et al. (2013a) note that simple matrix multiplications may be inaccurate because they include self-loops and cyclic paths in the propagation tree. They developed an algorithm based on multiplication of modified matrices to address this.

To summarise, an advantage of using matrix operations for CPA is their ease of implementation using standard mathematical software. However, these approaches are less adaptable than the approaches discussed earlier, for instance it may be difficult to extend them to account for some influences on change propagation or to consider different options for change implementation.

4.3.4 CP can be analysed by data mining

Approaches in this category utilise information about past changes and their propagations to predict the impact of proposed engineering changes. For example, Mehta et al. (2012, 2013) identify a set of attributes based on which similarity can be calculated, and then use them to compute the similarity between historical changes and a new change whose propagation is to be assessed. Lee and Hong (2018) elicit change patterns from historical change data and calculate the probability of change propagation in the form of a conditional probability distribution. Morkos et al. (2012) use textual analysis of a requirements database to analyse potential propagations at different numbers of steps.

A key advantage of data-mining approaches is that the data used for propagation analysis is grounded in how propagation actually occurred in the past, thus might be less influenced by modelling decisions than the model-based approaches discussed above. Further, with the use of machine learning algorithms, it may be possible to improve the prediction over time (Pan and Stark 2022). However, such approaches require large amounts of historical data. Systematic storage and retrieval of historical change data, therefore, is an essential prerequisite (Kocar and Akgunduz 2010). In addition, such approaches assume that future propagation will be similar to the past, however, historical data may become progressively less valid for CPA over time, due to accumulating changes in the design and design environment.

4.3.5 CP can be analysed by graph-theoretic analysis of a dependency structure

Approaches in this category apply graph-theoretic analysis to a modelled network of elements through which change can propagate. For instance, Li and Chen (2007); Chen et al. (2007); Li and Chen (2010, 2014) use clustering to identify patterns in a design's dependencies. They explain how this may enable identifying interfaces between clusters involved in change, thereby supporting control of the propagation scope. Cheng and Chu (2012) propose a method in which a complex design is considered to be a weighted network of design elements (parts, assemblies etc.). The authors propose the use of three indices for calculating direct, indirect and mutual impact of changes on those design elements. A similar complexity-oriented method was proposed by Li et al. (2008), in which nodes indicate parts and their complexities, while edges show connection strengths between parts. Ma et al. (2017) apply graph-theoretic measures such as in-degree to predict which items in a change network are most likely to receive or propagate changes.

An advantage of these approaches is that they typically require less information than the approaches discussed previously, in some cases only a binary network of dependencies. In consequence though, they do not account for the detail of specific changes and how they unfold over time.

4.3.6 CP can be analysed by manual tracing of change propagation

Some authors propose interactive CPA approaches in which change propagation is traced by a user, facilitated by a model of propagation dependencies. Flanagan et al. (2003) for example proposed a method in which propagation paths are traced on a matrix showing function-form relationships. Ahmad et al. (2013) developed a tool allowing a user to navigate the steps of propagation from changed requirements through to impacted design tasks, providing the possibility of exploring different ways of implementing the change and allowing interactive visualisation of their downstream effects. Ollinger and Stahovich (2004) created a tool called RedesignIT allowing investigation of different ways to adjust parameters to satisfy required functions and performance parameters. Conrad et al. (2007) rely on manual tracing of linkages in a CPM/PDD-based model to assess change impact and likelihood for an failure modes and effects analysis (FMEA)-style approach.

Interactive tracing of propagation is visually more intuitive than other (mainly numerical) methods discussed in this section. Interactive approaches allow users to bring their judgement to bear in a propagation analysis, guided by the information in a model. Arguably these approaches increase the usability of change propagation analysis (Ahmad et al. 2013) and may yield more accurate results, since the user can focus on the propagation paths most relevant to the case at hand. At the same time, the multitude of paths represented in typical CPA input data makes it difficult to comprehensively explore all possibilities.

4.3.7 CP can be analysed by fuzzy logic

The difficulty of ensuring accurate information has often been mentioned as an issue in CPA. One way to recognise this is to adopt a fuzzy logic-based approach, allowing imprecise input data to be handled explicitly. Ahmadinejad and Afshar (2014) use a fuzzy system to analyse change cost of elements in a system. The fuzzy system takes financial cost, time cost, number of iterations, etc. as input and the cost of change as the output. The cost of change is further used to seek the best change propagation path, accounting for cost. Although numerous applications of fuzzy logic can be found in different areas of design research such as in optimisation and dependency modelling, the technique has been less widely applied in the CPA context to date. This seems to offer a promising opportunity for further work.

4.3.8 CP can be analysed using CAD and CAD data

Simple propagation analysis is featured in some CAD software, for example detecting interference between components. Such approaches generally cannot assess the knock-on effects of changes and also do not consider non-geometric relationships that might propagate changes, such as functional relationships. Academic literature considering propagation approaches in CAD systems is also relatively limited. In one approach, Ou-Yang and Chang (1999) developed a framework with two modules to assist change management. The first module is based on a constraint network, whereas the second is based on defined spatial relationships, extracted from a CAD database, coupled with assembly methods. The two modules are combined together in a web-based query system for propagation analysis. Change impact analysis by assembly management also features in the work of Eltaief et al. (2017). These authors compare characteristics of initial CAD parts and modified CAD parts. The recorded changes are then propagated to the entire assembly once the modifications are reconciled according to the assembly definitions. A similar comparison-based approach is used for inter-domain propagation analysis by You and Chao (2009). Their approach considers different CAD formats keeping collaborative environments in mind, assessing change propagation by comparison of reference elements which are not identical. To summarise, some of the advantages and disadvantages of CAD-based approaches were previously stated in Sect. 4.1.5.

4.3.9 CP can be analysed by constraint satisfaction approaches

Some researchers apply classical constraint satisfaction problem (CSP) algorithms to support CPA. Yu et al. (2017), for example, proposed an approach in which propagation paths are searched based on a constraint satisfaction algorithm. They use a two-criteria method, in which one criterion measures change impact based on a dependency network, and the other criterion is based on cost. Constraint satisfaction is also used by Bauer et al. (2017), who develop a method to analyse impact of change on factory systems. Their method first identifies the changed items and the type of change, followed by a verification that the constraints are still satisfied. Depending on whether constraints are satisfied or violated, impact is calculated.

A second group of techniques use other methods to define constraints and relations between parameters. Xie and Ma (2016) for example use a feature-parameter association map to establish the constraint-variable relationships, which is then used to assess propagation based on constraint satisfaction. Yang and Duan (2012) discuss the concept of influence diffusion, in which changes in a parameter causes upstream parameters to change in order to satisfy parametric relationships based on constraint linkages.

An advantage of constraint-based CPA approaches is that they can yield specific quantitative insight regarding parameters of the design that are affected by a change at hand. However, representing more complex designs as CSPs is likely to be challenging. Large number of variables and constraints also mean that the solution of such problems is computationally intensive.

4.4 Visualising the results of CPA

The final category in the organising framework concerns visualising the results of CPA. Once CPA has been completed, the results must be visualised in a form that can be digested by the analyst and other stakeholders to support the ECM process depicted in Fig. 2. Approaches to do this are depicted in the bottom-right box of the framework in Fig. 1. Since each approach is suited to depict different types of information, a comprehensive presentation of CPA results may need to combine several visualisations. The next subsections discuss visualisation approaches used in the literature, alongside the information that is typically presented in them.

4.4.1 CPA results can be visualised as a matrix

The most common approach in this category is to use a DSM showing numeric information about how change introduced to a single element (on a row) may propagate and require change to every other element (on a column). The meanings of rows and columns may also be inverted. For example, Clarkson et al. (2004) and Jarratt et al. (2004) depict rectangles in the matrix cells, as shown in Fig. 9. The width and height of each rectangle indicates the impact and likelihood of change propagating between the pair of components, accounting for both direct and indirect propagation paths. Other researchers use a similar matrix with minor variations (Hamraz et al. 2012, 2013a; Pasqual and de Weck 2012; Zhang et al. 2020; Chen and Whyte 2021; Romli et al. 2018; Ren et al. 2021). An advantage of this visualisation is that it presents propagation effects for all possible change-initiating elements in a single static image; however, it does not show the reasons for the assessments (such as propagation paths that are involved) and cannot depict the outcome if multiple elements are changed at once.

4.4.2 CPA results can be visualised as a network diagram

When the objective is to depict propagation routes, a network diagram is often appropriate. Some researchers who adopt a network diagram for CPA input use colour to highlight computed propagation routes on that same diagram (e.g. Raffaeli et al. 2007; Wynn et al. 2014; Ma et al. 2016; Li et al. 2021b). Others generate automatically laid out networks to show propagation routes. For instance, Ahmad et al. (2013) visualise propagation networks as force-directed layout graphs that expand dynamically as the user explore possible outcomes of a change, while Luedeke et al. (2017) and Hoang et al. (2017a) depict propagation trees using partial rooted tree graphs. Another approach is to use focussed views that only depict part of a propagation network or allow the user to navigate CPA results to focus on specific information of interest. For instance, Yang and Duan (2012) and Ullah et al. (2017a) extract specific paths instead of showing them as part of the entire input network. Keller et al. (2005) present a propagation tree showing the component in which change is initiated, at the centre, while the affected components branch out radially. A variant due to Giffin et al. (2009) is shown in Fig. 10. In this diagram, the number of rings between each depicted component and the centre-left (initiating) component reflects the decreasing probability of the respective propagation path. Keller et al. (2005) proposed several other network-based techniques for visualising propagation networks resulting from CPA, including interactive fisheye layouts that depict propagation trees while reducing visually congested edges and a partially collapsed propagation tree, which enables a user to isolate the initiating and target components thereby focusing only on the paths of interest.

Overall, network visualisations can be helpful to present and explore propagation paths resulting from CPA, but are less useful to depict overall risks and options in a holistic way.

4.4.3 CPA results can be visualised as lists of affected elements

Where it is desired to present an array of propagation information with respect to each element or connection, lists or tables are oftenIf the change does propagate, its impact on appropriate. Examples of CPA output information visualised using lists include: Change cost (Ahmadinejad and Afshar 2014; Zheng et al. 2017; Ren et al. 2022); manufacturing impacts (Tseng et al. 2008); probability of change (Lee and Hong 2018); characteristics of change (Kattner et al. 2017); quality (Mckay et al. 2003); parameter convergence (Fan et al. 2004); magnitude of influence on assembly tooling (Yin et al. 2016); constraints violated or at risk of violation (Ollinger and

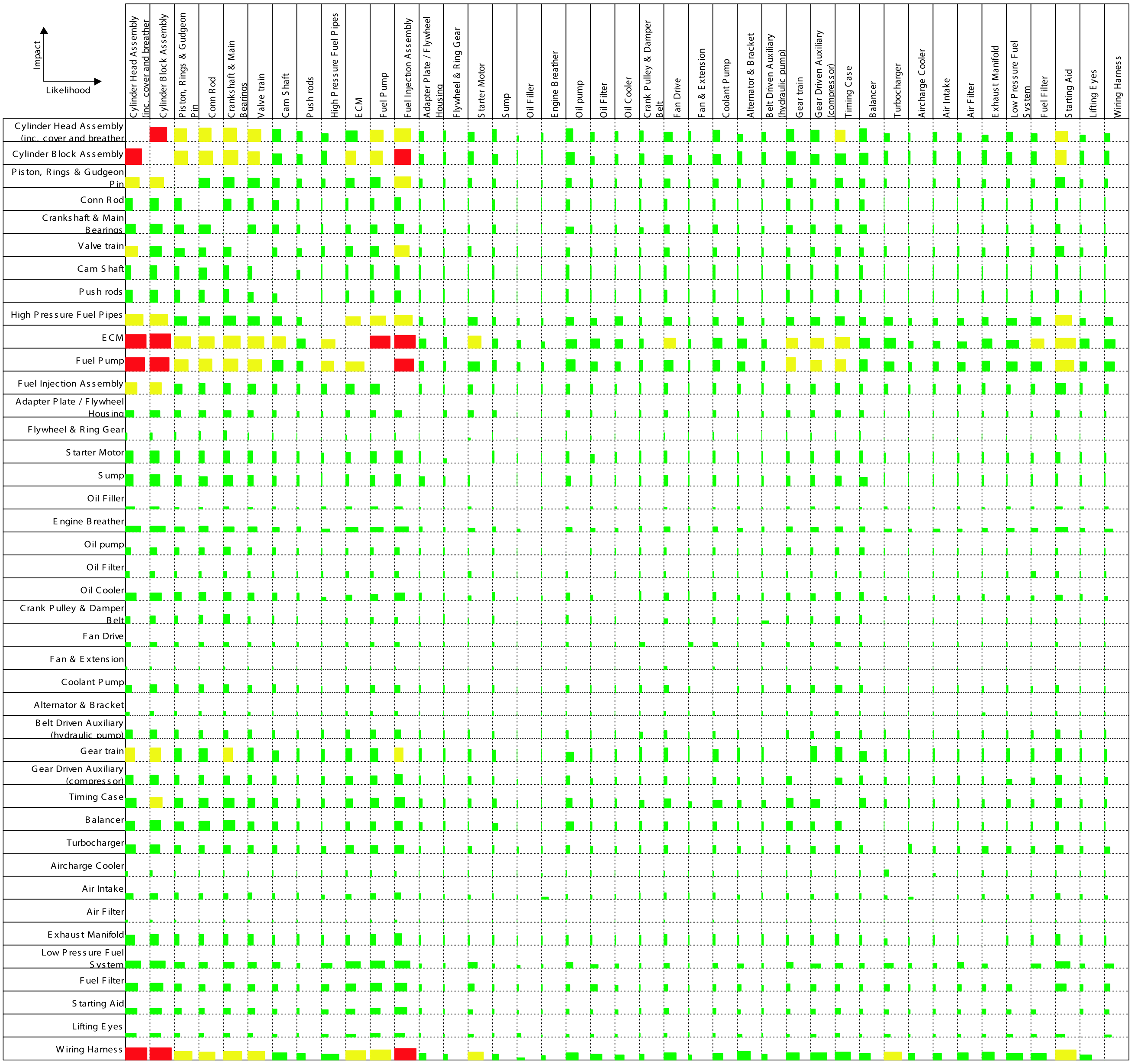


Fig. 9 Product risk matrix of a diesel engine, visualising output of the change propagation method (CPM). Reproduced from Jarratt (2004) with permission of the author

Stahovich 2004); parameters changed (Rouibah and Caskey 2003; Masmoudi et al. 2017b); propagation paths (Masmoudi et al. 2017a); risk assessments (Conrad et al. 2007; Koh et al. 2018); and impact magnitude (Chen et al. 2017). Fei et al. (2011) present a tabulated result interface which contains details such as the cause and effect of change, involved components, and suggested changes. Li et al. (2021c) and Liu et al. (2021) present the results of CPA analyses as lists of affected nodes. Similarly, Tang et al. (2010) use a table of interactions containing details such as level of interaction, cost, actors involved etc.

4.4.4 CPA results can be visualised as charts of change effects

Where it is desired to numerically compare options or routes, static 2D charts such as histograms, bar charts, graphs and so on are useful. Clarkson et al. (2004) for example present a case risk plot, on which components

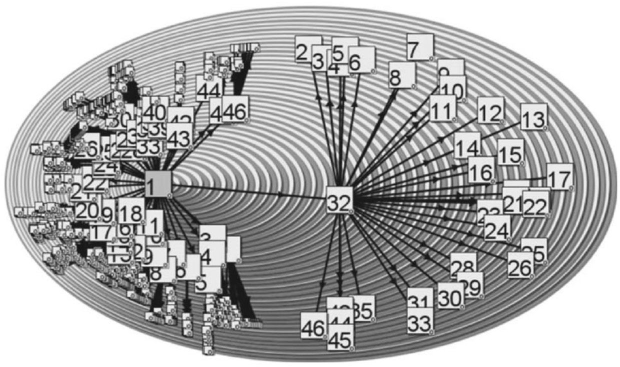


Fig. 10 Visualisation of a change propagation tree (Giffin et al. 2009), showing a change-initiating component highlighted in grey at the centre-left. An increasing number of rings between that node and each other node indicates a decreasing probability of that propagation route occurring. Reproduced with permission from ASME

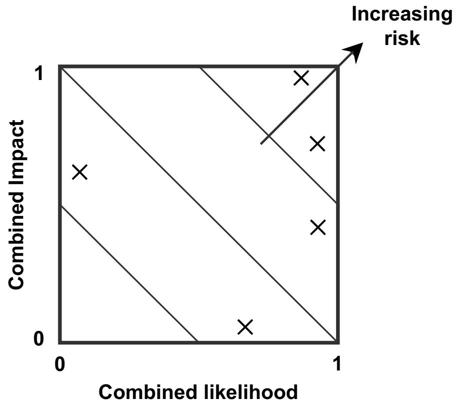


Fig. 11 Case risk scatter plot. The plotted points represent the subsystems potentially affected by propagation from a single change-initiating component (not shown). Reproduced from Clarkson et al. (2004) with permission from ASME

potentially affected by change propagation from a single initiating component are shown as points on a 2D scatter plot, where the axes represent likelihood and impact of the component receiving change (Fig. 11). Zhang et al. (2018) use charts to compare computed impacts when different changes are made. Li et al. (2012) and Li and Zhao (2014) use spider plots to present the likelihood of each computed path radially, while the paths themselves are placed circumferentially. Similarly, Yin et al. (2021) use spider plots to visualise the duration required to implement various change schemes.

To provide more examples, Plehn et al. (2016) and Rebentisch et al. (2017) show probability distributions of change cost resulting from CPA. Raffaeli et al. (2013) present change impacts based on four metrics in a bar chart, namely, assemblability, consumption, capacity and reliability. Schuh et al. (2017) present the accumulated probability of change vs different time intervals for each degree of freedom. Others use 3D plots—Ullah et al. (2018) for example depict change options against path distribution and number of distinct components affected using a 3D bar graph. These are just a few examples. Use of static charts to present CPA results is common in the literature.

4.4.5 CPA results can be visualised as charts of change effects capturing their evolution over time

Some CPA approaches predict the evolution of change effects over time, which is typically visualised using variations of a Gantt chart. For instance Chua and Hossain (2012) represent change effort by hatching portions of Gantt chart bars. Wynn et al. (2014) visualise possible change implementation processes using a probabilistic Gantt chart, in which density of colour indicates the probability of effort being required at a particular time while completing the redesign. They also highlight iterations in the redesign process using colour, as shown in Fig. 12. Other Gantt chart-based representations of change effects can be found in Maier et al. (2014), Leng et al. (2016), Yin et al. (2017a) and others.

4.4.6 CPA results can be visualised in CAD

Finally in this section, a number of authors visualise CPA results in CAD. Yin et al. (2016) for example represent changes to parts based on topology faces by marking the affected parts in red. Similarly, Kocar and Akgunduz (2010) apply traffic light colours to CAD parts to indicate the computed probability of change. Yin et al. (2017b) present detail

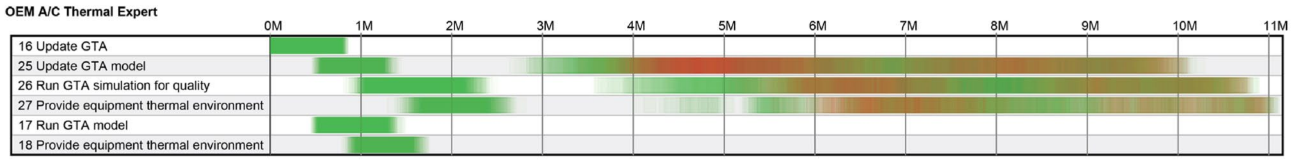
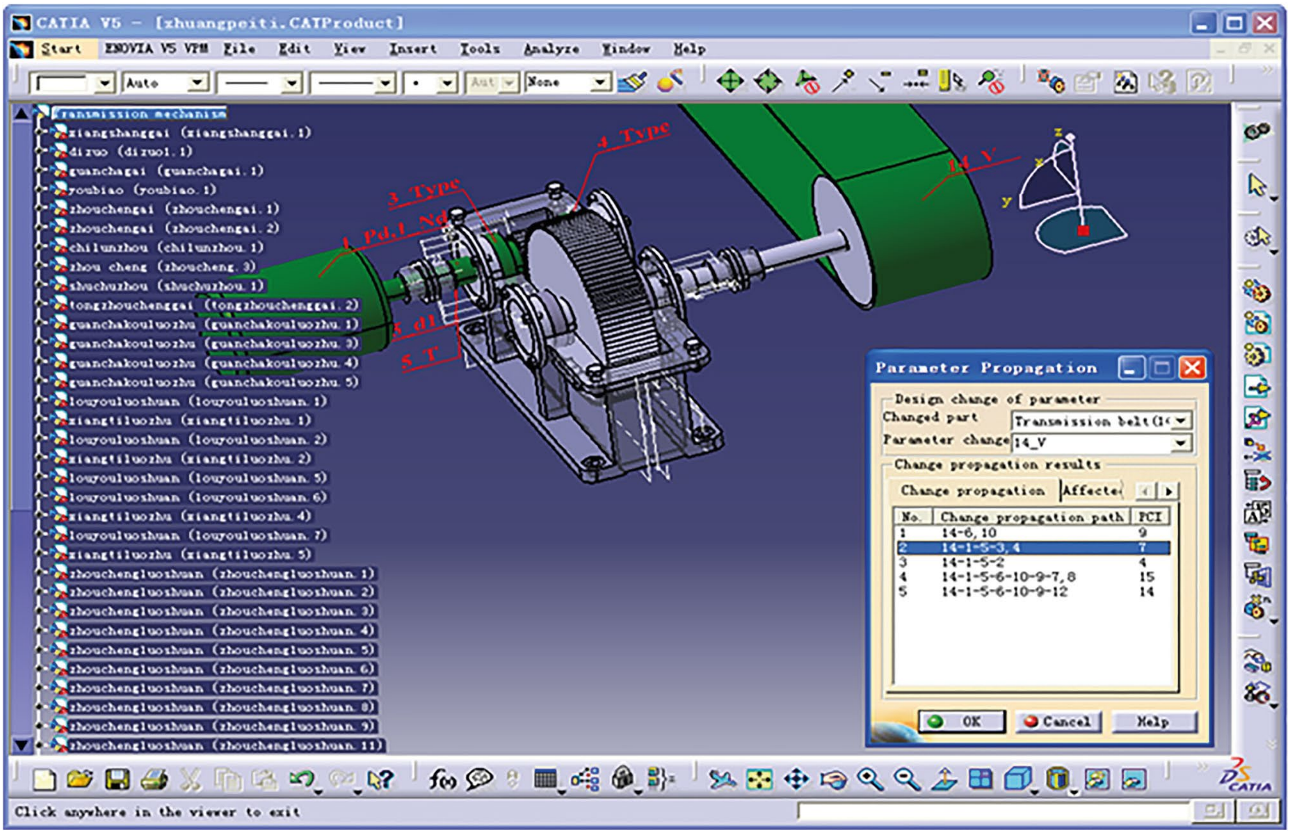


Fig. 12 Gantt chart of change implementation process as presented in Wynn et al. (2014). Green shows the first occurrence of a task, while red represents rework. Depth of colour represents the probability each task will be in execution at a given time. Reproduced from Wynn et al. (2014) with permission of ASME



Design change of parameter

Changed part: Transmission belt(1

Parameter change: 14_V

Change propagation results

No.	Change propagation path	PCI
1	14-6, 10	9
2	14-1-5-3, 4	7
3	14-1-5-2	4
4	14-1-5-6-10-9-7, 8	15
5	14-1-5-6-10-9-12	14

Fig. 13 Changed parts visualised as annotations in a CAD environment. Reproduced from Yin et al. (2017b) with permission from ASME

of computed change effects to e.g. parameters and topology faces using a dialog box in the CAD software (Fig. 13). Ma et al. (2008) use dialog boxes to notify the CAD user of constraint violation relating to a change, which can then be used to choose between options to satisfy the constraint(s). You and Chao (2009) present a changed part and the original part side by side allowing the CAD user to visually compare them. To summarise, visualising CPA output in CAD (and more generally integrating CPA with CAD) appears to offer great potential for improving the take-up of advanced CPA approaches from research into engineering practice.

5 Visualising the topology of the literature

Having completed discussion of the individual concepts of our framework throughout Sects. 3 and 4, this section provides a more integrative view by discussing the overall topology of the CPA literature. This is done through a visual analysis.

The reviewed literature was first revisited to classify each of the 143 CPA publications included in our review according to the categories of the organising framework. Most of the analysed publications were possible to assign to one or more key concepts in each of the categories (boxes) shown in Fig. 1. This resulted in a table that maps the 143 computable CPA approaches (as reported in specific publications) against the 50 key concepts of our framework. To verify the table it was then cross-checked with the review text, leading to some adjustments. Although care was taken when preparing and checking the classification, it should also be noted that (as in any such analysis) there was a need for interpretation in classifying some of the papers. The completed classification table is included as Supplementary Material accompanying this article.

The classification data were analysed by generating visualisations to reveal the topology of the literature. A range of visualisations were generated and four of the most insightful were selected for inclusion in this article. The four visualisations, in sum, address the following questions:

- How is each use case addressed by combining particular concepts and theories of change propagation? Where might there be opportunities for research to explore how concepts and theories can be combined in different ways to address use cases?

- How similar are the use cases for CPA, in terms of the combinations of key concepts that have been used to address them?
- How are the key concepts combined in literature to form CPA approaches? What are the main clusters of key concepts adopted by CPA literature?

5.1 Visualising the data representations and analysis techniques used to address use cases for CPA

Generating the visualisation. Sub-matrices for each category were first extracted from the classification table. For example the sub-matrix for the *use cases* category has 7 columns, one for each of the seven key concepts (Sects. 3.1.1 to 3.1.7), and 143 rows, one for each publication.

If A and B are the sub-matrices for two categories, having n rows (papers), and m and p columns (concepts), respectively, the number of papers common to each pair of concepts can be calculated by matrix multiplication:

$$C = A^T \cdot B \tag{1}$$

The resulting matrix C has m rows and p columns, with the entries representing the number of papers that address each pair of key concepts. Three such matrices were computed, for comparing Sect. 3.1 against Sect. 4.1; Sect. 4.1 against Sect. 4.3; and Sect. 4.3 against Sect. 4.4. The three matrices were used to generate a Sankey diagram, which is shown in Fig. 14.

Insights. Figure 14 shows the number of publications addressing each key concept in each of the depicted categories of our framework (the height of the bars), and also the numbers of publications that combine key concepts (the width of the connecting lines) in categories that are adjacent.

In terms of number of publications addressing concepts individually, the diagram reveals that the largest number of approaches address the use cases of assessing the impact of proposed changes on a design (Sect. 3.1.2) or assessing the cost, time and effort of those changes (Sect. 3.1.4). Relatively few papers address the impact of changes on product families and on production systems; the importance of these design considerations in engineering practice suggests the corresponding use cases could be promising areas for future work. Similarly, it can be observed that analysis methods deserving further attention are data mining (especially considering the rising awareness in many companies of the value of data) and fuzzy logic-based approaches (because as mentioned earlier they are, in principle, well-suited to handle the uncertainties endemic to CPA). Finally, it can be observed that very few approaches leverage data from CAD or present output in CAD systems; as noted earlier we suggest that integration with CAD is a promising area for future research in CPA.

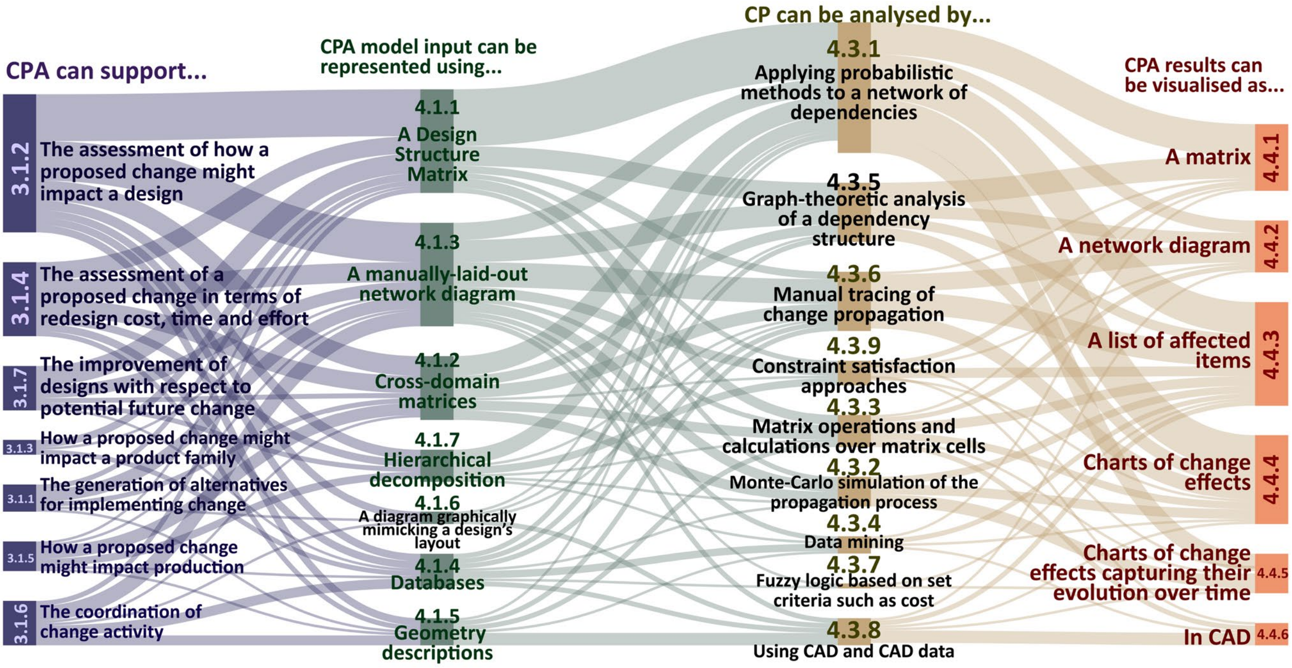


Fig. 14 Sankey Diagram in which bar heights show the relative number of papers addressing each use case for CPA, each input visualisation, each analysis technique and each output visualisation. Line thicknesses connecting the bars indicate the relative numbers of papers that combine the respective pairs of key concepts

Secondly, in terms of the ways that the depicted concepts are combined, it is clear in Fig. 14 that, for example, the greatest proportion of papers addressing the top-most use case do so using a DSM or network-based visualisation, combined with path combination techniques for analysing propagation. It can also be seen that the techniques used for visualising the results of any particular analysis approach are relatively evenly distributed, whereas some input techniques are more strongly correlated with certain analysis techniques than others. This difference reflects that most approaches use multiple output visualisations to present different aspects of the computed propagation data, but only a single input representation. Perhaps future work could investigate using multiple views of CPA input information, which might help to create more comprehensive data sets for CPA and help to visualise and verify that input information.

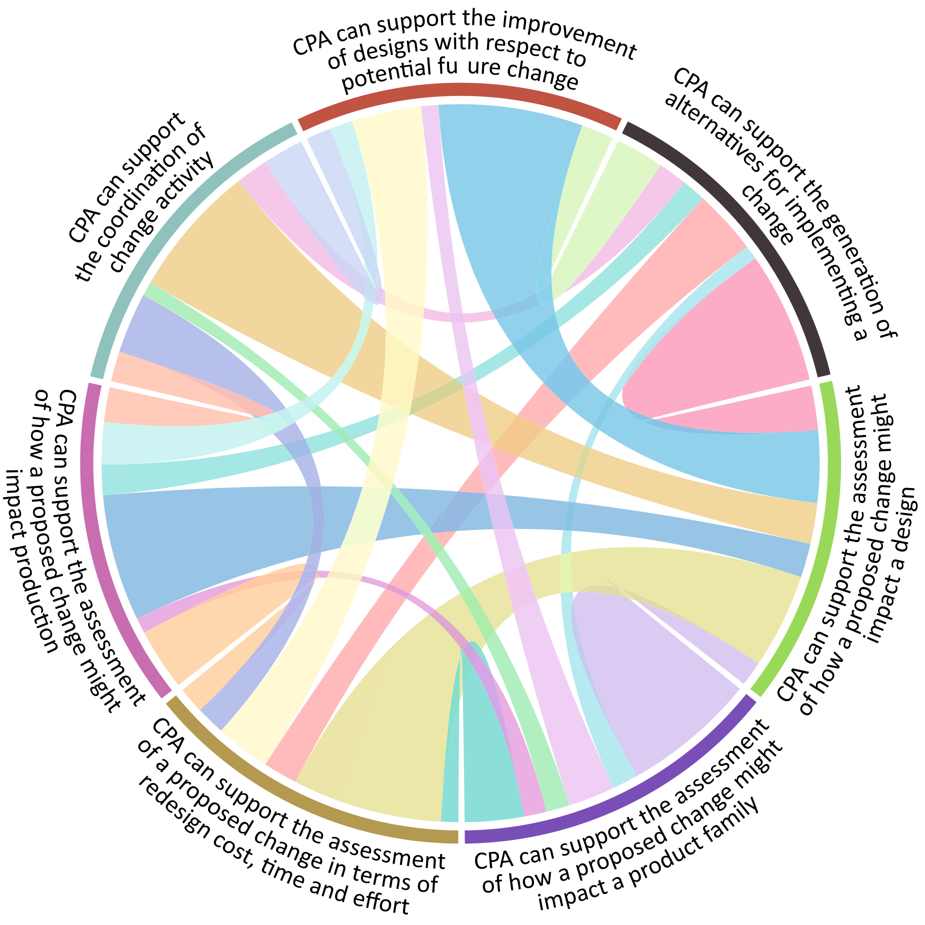
5.2 Visualising the similarities between use cases

The second analysis to be discussed concerns the similarities between use cases for CPA, in terms of the combinations of key concepts used by researchers to address them.

Generating the visualisation. The similarity between each pair of publications was first computed by counting the number of common sub-categories. The resulting pairwise comparison values, that could in principle range from 0 to 50 (since there are 50 key concepts in our framework) were placed in the cells of a 143 × 143 matrix. This matrix was further processed to generate a 7 × 7 square matrix in which the row and column headers represent the seven use cases of our framework and the numbers in the cells represent the similarity between each pair of use cases. To achieve this, papers in the 143 × 143 matrix were grouped according to the use case addressed. For each use case pair, the values from the relevant rows of the 143 × 143 similarity matrix were summed and entered into the 7 × 7 use case matrix. Finally, the latter matrix was used to generate a chord diagram as presented in Fig. 15. Note that the diagram is normalised such that every use case (around the perimeter of the circle) appears at the same size, in order to show the relationships as proportions regardless of the number of papers addressing each use case.

Insights. The insights to be drawn from Fig. 15 relate to the relative thicknesses of the bands emerging from

Fig. 15 Chord diagram showing the similarity between use cases for CPA, in terms of the key concepts that are combined to address them



each depicted use case; a thick band indicates that a pair of use cases are commonly addressed by similar combinations of key concepts, whereas a thin band indicates the opposite. For instance, the use case pertaining to the assessment of change in terms of redesign cost, time and effort (Sect. 3.1.4) and the use case involving assessing the impact on design (Sect. 3.1.2) are revealed to be addressed by relatively similar methods, which will not be surprising to readers familiar with the reviewed approaches. On the other hand, there is weak similarity between approaches used to generate alternatives for handling a change and those to assess change impact on a product family. One insight is that future research should consider how these use cases could be combined in CPA approaches; similar conclusions could be drawn by examining other weakly connected use cases in Fig. 15.

5.3 Visualising the design domains and influences on change propagation considered when addressing each use case

This subsection addresses the question of what design information domains and influences on change propagation are considered in literature addressing each use case.

Generating the visualisation. The subset of papers addressing each use case was divided into the papers considering each domain, and then further subdivided into the influences on change propagation considered in each paper. The result is visualised as a hierarchical map in Fig. 16, in which the area of each rectangle indicates the total number of papers addressing each combination of key concepts. Note that a single paper can appear in multiple boxes of the map, if it addresses more than one key concept in any of the three categories considered.

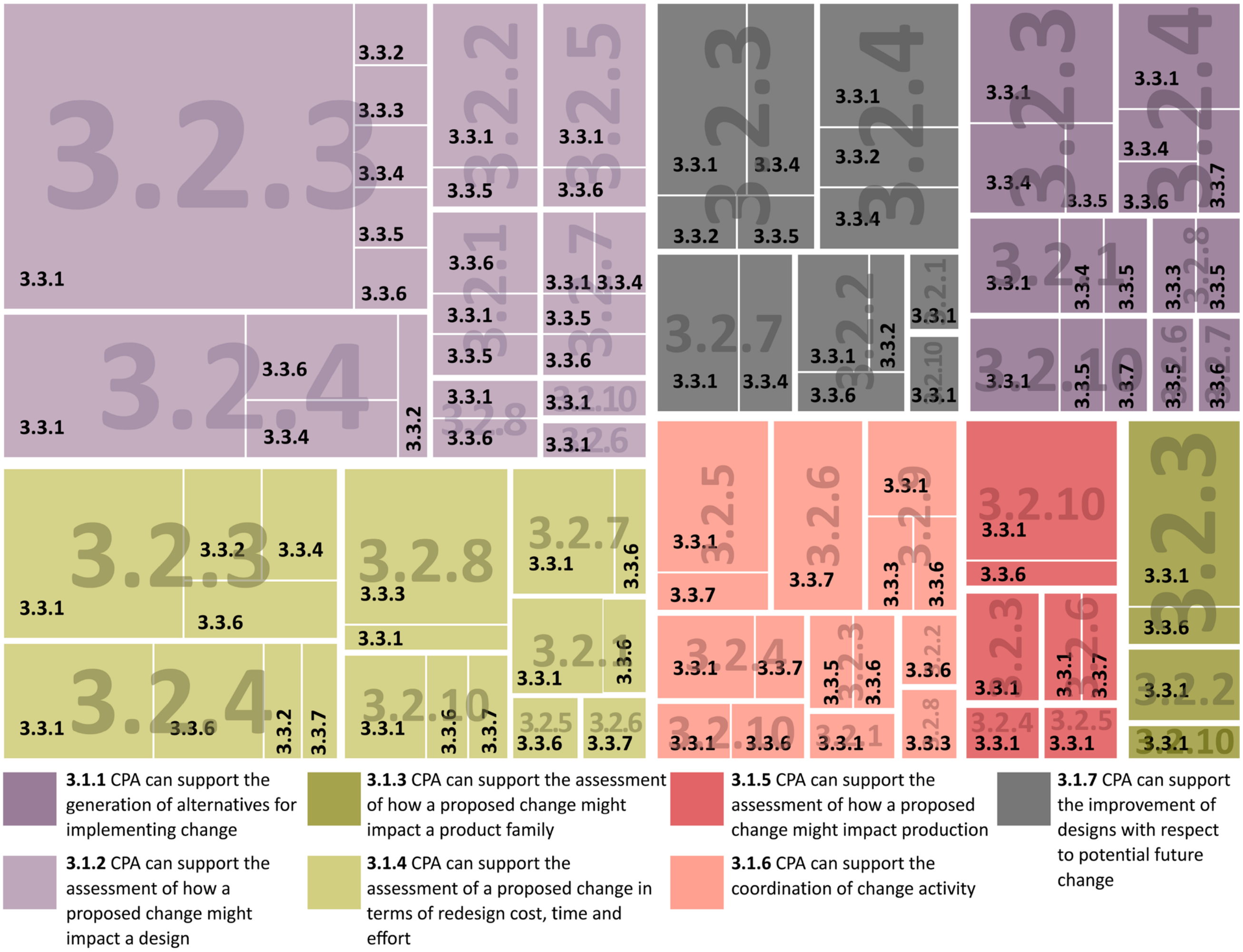


Fig. 16 Hierarchical map decomposing the seven use cases for CPA (at the top level) into the information domains (second level of decomposition) and the influences on change propagation (third level of decomposition) that are considered by approaches that address them. The area of each rectangle represents the relative number of publications combining the three key concepts discussed in the indicated sections

Insights. It is clear from the relative areas of the rectangles in Fig. 16 that some use cases have received substantially more research attention than others (as is also visible in Fig. 14). Furthermore, the large area of the top leftmost rectangle clarifies that more research has addressed the combination of assessing the impact of change on a design (Sect. 3.1.2), through analysis in the components domain (Sect. 3.2.3) considering the impact of dependency properties on how change propagates (Sect. 3.3.1) than any other combination of concepts in the three categories under consideration. At the other end of the spectrum, the rectangle at the bottom right of Fig. 16 confirms again that very few papers address the use case of Sect. 3.1.3 (assessing change propagation impact on product families) and adds insight by showing that those that do, do not fully explore the space of possibilities in terms of the domains of propagation (only Sect. 3.2.2, functions, Sect. 3.2.3, components/subsystems, and Sect. 3.2.10, manufacturing and other lifecycle phases, are considered); or in terms of the influences on change propagation (only Sect. 3.3.1, properties of connections, and Sect. 3.3.6, designer choices) are considered. Nevertheless other domains and influences are clearly relevant to this use case. Considering the importance of product family considerations in much of product development practice, we suggest this relatively lightly explored use case deserves additional attention. Other relatively unexplored topics can similarly be identified by examination of Fig. 16.

5.4 Visualising clusters of literature that use similar context, theory and approaches

The final analysis to be discussed concerns the main clusterings of research work in literature.

Generating the visualisation. A similarity matrix was first created along similar lines as described in Section 5.2. However, before the similarity matrix was computed, the classification table was sequenced in chronological order so that papers published earlier appear at the top and latest papers appear at the bottom of the table. Secondly, a condition was applied on the comparison such that two papers would be compared only if the second paper was published after the first. This produced a 143 × 143 upper triangular matrix. The Gephi clustering and layout algorithm was then used to produce a directed graph, that is shown in Fig. 17. The radii of the nodes represent the out-degree of each paper, a measure that combines the number of later publications

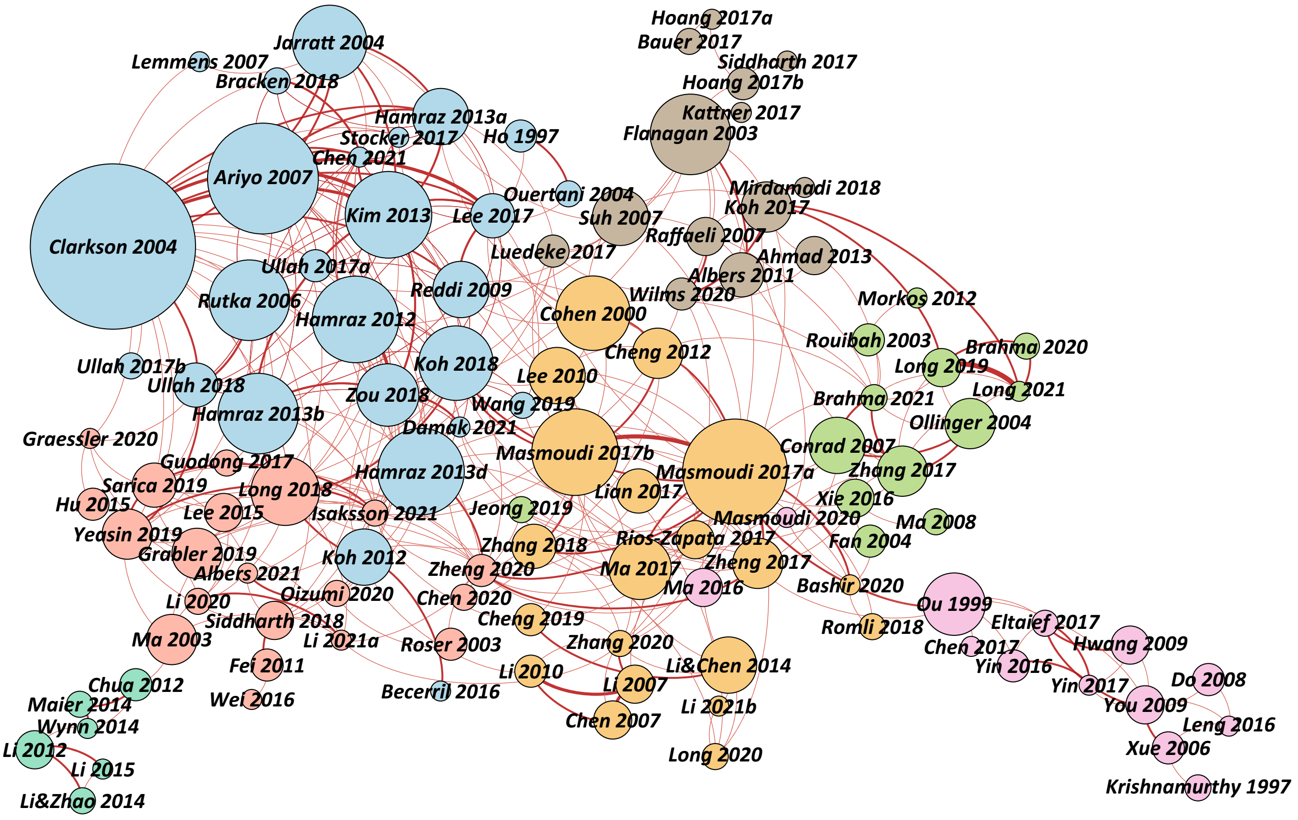


Fig. 17 Clusters of literature on change propagation analysis. Each arrow connecting a pair of papers indicates high similarity in terms of context, theory and approach adopted. Larger nodes indicate that the corresponding paper has high similarity to a large number of subsequently published papers

and their similarities to the paper at hand. The thickness of each edge shows how similar the respective pair of papers are. Note that papers and edges with weak similarity were filtered from the diagram, which was required to reduce clutter and achieve visual separation of clusters.

Insights. The figure overall shows the popularity of the probabilistic methods clustered at the centre, especially to the early development of the field. Recall that larger nodes represent publications that were subsequently followed by many other papers with high similarity (note that this does not consider whether a paper is highly cited). Several large nodes stand out, most notably the seminal paper of Clarkson et al. (2004), concepts from which were later adopted in many other papers.

The clustering algorithm also produced a modularity index, based on which a colour palette was applied to the nodes. The emergent clusters can be observed to reflect known focus areas in the research community. For example, the cluster shown in blue containing Clarkson et al. (2004), Jarratt et al. (2004), Hamraz et al. (2012), etc., all either use the CPM method or are similar to it, while the cluster of papers on the bottom left (in green) are process-based propagation approaches—the figure shows these are quite distinct in the concepts they adopt from the purple cluster on the bottom right, which contains manufacturing- and CAD-oriented approaches. One suggestion for further work is to explore possibilities to carry insights between the more disjoint clusters.

6 Discussion and outlook

6.1 Recap of contributions

To recap, this article has contributed a literature review of computable models for change propagation analysis, extracting key concepts from that literature and organising them into a framework. As well as discussing the concepts individually, a visual analysis of the literature has been presented. The framework and review of concepts summarise current state-of-the-art in change propagation analysis, while the visual analysis complements this by providing a more holistic overview of the research area.

6.2 Suggestions for further work

Several opportunities for further work were already suggested in the discussion of the visual analysis in Sect. 5. In this section, some additional suggestions are provided.

The first area that deserves further research attention is the evaluation of change propagation approaches. Some years ago, Ahmad et al. (2013) found that most papers presenting such models only discussed limited efforts at evaluation. To explore this further, we revisited the reviewed publications to identify evaluation approaches used by researchers in each case. Table 1 summarises the findings in terms of evaluation approaches used and the number of publications adopting each. This table reveals that the majority of papers demonstrate CPA approaches using case studies developed by the respective researchers in the university setting, without reporting an empirical evaluation involving any participants apart from the researchers. Therefore, we suggest that further work to evaluate existing approaches might yield insight for their improvement. A related opportunity is to undertake an empirical comparison of some of the many CPA approaches to determine which is the most effective in practice.

We also observe that while the stated motivation in most CPA research papers is to tackle changes in complex designs, the same papers rarely present evaluations at the scale of situation at which they are intended to apply. While recognising that large-scale evaluations are often not possible for researchers for reasons of time and access, lack of evaluations in complex industrial settings remains a limitation of CPA research that should be addressed in future.

Other opportunities for further work concern further development of CPA methods and their applications. The suggestions in the following paragraphs have already been considered to some extent in literature, but in our view are promising areas for further development.

One opportunity is to investigate how the insights and approaches developed to support CPA in the engineering change management context could be translated or adapted

Table 1 Evaluation of CPA approaches in literature

Evaluation approach reported	#papers
Little attempt at evaluation is apparent	6
Logical argument and positioning against prior publications	16
Approach illustrated by application to an example developed by its authors	70
Approach illustrated with an example from industry, without explicit empirical evaluation	32
Approach evaluated using a laboratory experiment involving other parties, e.g. students	4
Preliminary evaluation in an industry context and practitioner feedback collected	15
Approach deployed in industry and ongoing successful use by practitioners is reported	0

to other situations, for instance to support the management of design iteration and rework, and to support the analysis of propagation effects outside the engineering design domain. Another opportunity is to investigate the handling of design evolution in CPA models. Many models are based on eliciting a model of the design at a fixed point in time and little attention is given to updating the model as the design evolves (Hamraz et al. 2013a). This is likely to be of more concern for detailed (e.g. parameter level) approaches than for those which consider propagation through more abstract domains like functions. Some consideration of evolving dependency structures is provided by e.g. Yu et al. (2017) and more recently, dynamic change probabilities are discussed by Long and Ferguson (2018), Long and Ferguson (2020), and Li et al. (2021a). However, the majority of reviewed approaches do not explicitly address this issue.

Change propagation analysis could also be further investigated as an approach to support Design for X. For instance, change propagation would be of concern when modifying of a design to integrate additional environmental or lifecycle considerations. The change could propagate with respect to the information domains reviewed in this article, but also could propagate with respect to the design issues themselves (for instance, changing a part to use a different manufacturing technology might have implications on its lifecycle properties). A closely related opportunity is to more comprehensively explore how CPA can support adoption of advanced manufacturing technologies by analysing the design changes and other changes required. As previously highlighted, research in design change propagation that explicitly considers manufacturing systems is relatively sparse, but the topic has seen gradually increasing interest in recent years.

Also, relating to manufacturing, CPA approaches could be further developed to help manage the effect of design changes to the supply chain of a product. OEMs dealing with complex engineered products often have global supply chains with a multitude of suppliers with very complex supply chains. Design changes, therefore, may propagate and potentially disrupt such supply chains and cause significant production delays. While some researchers have reported case studies that highlight this issue, as mentioned in Sect. 3.2.10, there remain opportunities to develop CPA approaches to assess the effects of changes on the supply chain.

Another emergent field is the use of design margins in change propagation assessment research. Margins play an important role in determining whether changes will propagate or get absorbed, therefore, quantification of margins could help to assess where and how changes propagate. While the topic has gained some attention recently (Long and Ferguson 2019, 2021; Brahma and Wynn 2020), significant gaps remain.

Finally, we believe there is value to further explore exploitation of data in CPA approaches. As discussed earlier in this article, some publications do investigate the use of data mining and similar techniques for CPA (e.g. Mehta et al. 2012, 2013; Kocar and Akgunduz 2010), but the number of such approaches is relatively small thus far. With increasing introduction of advanced digital technologies in design and manufacturing and an increasing awareness of the value of data, it seems likely that data-analytic approaches to CPA will become increasing viable. A related issue is to investigate how the emerging applications of digital twins in engineering design could be leveraged to assist change propagation analysis in those designs.

6.3 Concluding remarks

Design change is ubiquitous in engineering practice. Computable approaches to change propagation analysis have great potential to improve the handling of such changes. Many such approaches have been developed and reported in research literature, based on a smaller number of key concepts. The framework presented in this article extracts and organises those key concepts. There are numerous avenues for future research to develop change propagation analysis approaches and to apply them to new problems and domains. Overall, it is hoped that this article will convey the current state of the research area and will be of use to position future developments.

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