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a systematic literature review

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REVIEW ARTICLE

Platform-based Product Development in the Process Industry: A Systematic Literature Review

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Abstract

Platform-based product development has been applied extensively in discrete manufacturing industry to accommodate changing market demands. Nevertheless, while process industry manufacturers face similar market demands, the topic is only sparsely covered in literature. Through a systematic review of the literature, this study uncovers the definitions used, drivers behind, approaches and methods applied, and industry examples of platform-based product development in the process industry. Based on these analyses, a research agenda is then proposed to further the knowledge of this topic. The study identified existing definitions of key platform-related terms used in several studies and furthermore discovered new definitions for some terms. The most prominent drivers behind pursuing platform-based product development was found to be cost reduction and productivity of product development, with development lead time reduction playing a less significant role. Literature related to platform-based product development focuses primarily on product design and development issues, with less attention given to market, manufacturing, and supply chain issues. Only few industrial cases were identified within the process industry while multiple anecdotal descriptions were discovered. For future research, further insight into key platform concepts, applicability of existing methods, broader value chain focus and detailed industrial cases are considered relevant.

KEYWORDS

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process industry; non-assembled products; product platform; product development; variety management

1. Introduction

Since the golden age of mass production in the mid-twentieth century, markets have shifted towards offering higher product variety with ever shorter product life cycles to satisfy customers, resulting in markets becoming increasingly saturated (Koren 2010). These market changes are almost ubiquitous in that they are experienced across industries affecting not only manufacturers of assembled products, e.g. cars (Simpson, Siddique, and Jiao 2006), but also manufacturers of non-assembled products, e.g. food (Fuller 2016). These market dynamics cause an increase in the external complexity experienced by manufacturers which in turn respond with more product varieties with ever increasing frequency on a globalised playing field (Vogel and Lasch 2016; Seifert et al. 2013). To accommodate these changes, manufacturers increase their internal complexity to stay relevant to their customers (Vogel and Lasch 2016). However, doing so comes at the expense of higher costs, less efficient processes (Piya et al. 2017) and, consequently, reduced competitiveness. A proven response to this challenge is the adoption of platform-based product development principles. This approach to product development is based around a simple key challenge: balancing the trade-off between customer perceived distinctiveness in product offerings and the commonality of these product offerings from the perspective of the company (Simpson, Siddique, and Jiao 2006; Pirmoradi, Wang, and Simpson 2014; Meyer and Lehnerd 1997). This may be achieved via product platforms, which are designed so that derivative products, each targeting a specific market segment, can be efficiently manufactured from a common base of assets (Meyer and Lehnerd 1997; Ulrich, Eppinger, and Yang 2020). In platform-based product development, the product architecture determines how individual elements of the product are structured and interact (Meyer and Lehnerd 1997). Most commonly, product architectures are comprised of modules, each of which seek to encompass the entirety of a function (Ulrich, Eppinger, and Yang 2020). Such architectures facilitate changing of modules to accommodate different customer needs through standardised interfaces, which govern the interaction between modules. Based on these concepts, product platforms and product families are formed.

1.1. *Potentials and challenges in platform-based product development*

The interest in platform-based product development comes mainly from the aforementioned ability to attain competitiveness by successfully balancing internal complexity against external complexity.

Looking outside of a manufacturing company to the potentials and challenges related to external complexity product platforms can:

- be strategically important towards gaining market shares (Simpson, Siddique, and Jiao 2006) such as by servicing otherwise unprofitable market niches (Ulrich, Eppinger, and Yang 2020).
- assist in improved new product launch speed (Vickery et al. 2015), thereby beating competitors to market.
- help achieve network effects from both customers and suppliers (Ulrich, Eppinger, and Yang 2020), thereby increasing e.g. longevity of the platform.
- increase the risk of vertical cannibalisation within a product line due to perceived insufficient differentiation between high-end and low-end product variants (Simpson, Siddique, and Jiao 2006).

Platform-based product development also has several benefits with regards to the internal complexity and manufacturing in particular, where they have been reported to achieve:

- increased flexibility and utilisation of production facilities (Simpson, Siddique, and Jiao 2006).
- improved product quality and reduced waste (Pirmoradi, Wang, and Simpson 2014).
- increased efficiency and reduced costs in manufacturing (Liu, Wong, and Lee 2010; Ben-Arieh, Easton, and Choubey 2009) and inventory management (Galizia et al. 2020; Ulrich, Eppinger, and Yang 2020).

- improved economies of scale through increased commonality across product variants (Pirmoradi, Wang, and Simpson 2014; Meyer and Lehnerd 1997; Park and Simpson 2008) with resulting cost savings as high as 30 percent (Cameron and Crawley 2014).
- reduced capital investments in manufacturing by up to 50 percent (Muffatto 1999) and likewise reductions in lead time (Cameron and Crawley 2014).

Besides manufacturing related benefits, platform-based development approaches also influence product development activities, both positively and negatively, by:

- simplifying development of derivative product variants (Ulrich, Eppinger, and Yang 2020).
- facilitating product and platform upgrades, thereby speeding up innovation and generational evolution (Simpson, Siddique, and Jiao 2006; Aydin and Ulutas 2016).
- reducing testing and certification costs for complex products through module reuse.
- increasing unit cost for low-end products due to component sharing across market tiers (Simpson, Siddique, and Jiao 2006; Bhandare and Allada 2008).
- increasing initial development costs by up to 10 times (Ulrich, Eppinger, and Yang 2020) for new platform development projects.

1.2. *Industry examples of platform-based product development*

Although there are potential drawbacks associated with adopting platform-based approaches to product development, the potentials outlined above have contributed to many companies from various industries recognising the strategic value of product platforms. Over 20 examples of companies utilising product platforms were identified in the studies cited in this section, ranging from automotive and aeronautics products to power tools and household appliances. While the studies in this section are far from an exhaustive ensemble of the literature on platform-based product development, only a few brief mentions of platform-based products from process industries are mentioned in the sources cited. This is despite the process industry accounting for more than 50 percent of the USA's total manufacturing output with food, beverage, and tobacco; petroleum and coal; and chemical products making up the three highest grossing industry sectors (Nicholson and Noonan 2014). Examples provided from the process industry are Intel's platform-based chipsets (Ulrich, Eppinger, and Yang 2020) and 3M's post-its (Meyer and Lehnerd 1997). If this sample is indicative, there appears to be a profound lack of studies and examples of platform-based product development in a process industrial context. From the authors' experience, this indeed applies to most literature on the subject.

1.3. *Comparing discrete and process manufacturing industry products*

Manufactured products can typically be distinguished based on their industry of origin, adhering to either discrete or process manufacturing industry (Flapper et al. 2002). Depending on the industry of origin, products and their production processes often share certain characteristics, some of which are unique to the given industry while others are more general. This section will therefore briefly introduce the two industries and devote special attention to elaborating on the characteristics related to process industrial manufactured products. Generally, definitions of the process industry take one or more of three perspectives, where the industry is defined by:

- The types of processes typical to the industry (continuous, batch, mixing, blending, forming, baking, extrusion, etc.) (Zhu et al. 2018; King et al. 2008; Abdulmalek, Rajgopal, and Needy 2006)
- The characteristics of the products manufactured (solids, powders, slurries, liquids, gases, sheets, rolls, etc.) (King et al. 2008; Dennis and Meredith 2000)
- The subsectors of the industry (chemicals, food and beverages, metals, minerals, pharmaceuticals, pulp and paper, steel, etc.) (Samuelsson, Storm, and Lager 2016)

Depending on the specific definition adopted, either a narrower or broader perspective on the process industry is taken. Regardless, most studies on process industry characteristics note that a distinguishing trait of products inherent to this industry is that they are continuous instead of discrete – i.e. measurable rather than countable

(Lyons et al. 2013), such as milk, cement, or flour. Even so, several studies note that most continuous products become discrete at some point during manufacturing (Dennis and Meredith 2000; Abdulmalek, Rajgopal, and Needy 2006; King et al. 2008). Several characteristics broadly defining the nature of process industry products have been compiled in Table B1. For further detailed discussion on the characteristics of process industry products the reader is referred to the works of Dennis and Meredith (2000); Abdulmalek, Rajgopal, and Needy (2006) and King et al. (2008).

[Table 1 about here.]

Recognising the differences and unique characteristics listed in Table B1, multiple questions concerning the feasibility and potential of platform-based product development in the process industry arises:

- Does the, often simpler, bill-of-material structures seen in process industry products affect the potential benefits?
- Is the typically non-assembled nature of process industry products a hindrance towards applying methods originally developed in the context of assembled products?
- How does limited storage time of products and semi-manufactures impact the ability to adopt usage of platform development and modularity in design?
- Are regulatory constraints impeding companies' ability to offer customisable products?
- How should residual products - whether co- or by-products - be handled in platform development and leveraging?

Despite discrete manufacturing industry products and process manufacturing industry products experiencing similar market conditions, the unique challenges related to the latter, may provide an explanation for the lack of industry examples available from the process industry.

1.4. *Research questions*

Based on the introduction, it is apparent that traditional product development and manufacturing approaches are unfit for today's ever-increasing market needs. This was shown to be the case regardless of whether the manufacturer is in the discrete manufacturing or process manufacturing industry. Examples from literature and industry alike showed that platform-based product development has proven a successful approach for accommodating the needs and challenges of today's markets. Even so, documented examples of platform-based product development approaches from the process industry are very sparse. This is despite evidence suggesting that this industry may also derive benefits from adopting platform-based approaches to product development. Based on these preliminary findings, the research question for this study is defined as:

> How does platform-based product development apply to the process industry?

To support the answer to the overall research question, several supporting subquestions have been formulated:

RQ1: What definitions related to key concepts in platform-based product development in the process industry are presented in identified literature and how do these definitions relate to those from discrete industry?

RQ2: What drivers of platform-based product development in process industry are described as being essential in pursuing this approach?

RQ3: Which methods and approaches are applied for tackling issues related to platform-based product development in the process industry?

To answer these questions, the rest of this paper is structured as follows. Section 2 describes the methodology of the study. Next, Section 3 presents bibliometric analysis results of the included studies. Following, in Section 4, definitions of key subject terms are introduced after which Section 5 follows up by addressing the second research question concerning drivers of platform-based product development. Section 6 then presents an analysis of the approaches and methods identified for issues related to platform-based product development. Following, Section 7 discusses the findings and Section 8 presents implications of the findings for practitioners. Section 10 summarises the most relevant topics for further research. Lastly, Section 9 concludes on the findings of study.

2. Methodology

Literature reviews as a research methodology are well suited for advancing the knowledge within a given field of study (Snyder 2019; Kitchenham 2004; Paré et al. 2016; Hart 1998; Levy and Ellis 2006). They do so by extensively covering the available knowledge within a scientific field or topic, thereby creating an understanding of the topic (Hart 1998), and identifies patterns and gaps to direct future research activities towards relevant scientific aspects. Nevertheless, literature reviews are performed very differently. A widely recognised approach to ensure trustworthiness and quality of a literature review is to perform a systematic literature review (SLR) as these are often characterised by their rigour and thoroughness (Levy and Ellis 2006; Kitchenham 2004; Snyder 2019). Thus, in line with the research questions posed for this paper, SLR is chosen as the review methodology for this paper. The remainder of this section will cover relevant aspects of the SLR methodology applied for this study including the review process, search terms, resources searched, and study selection.

2.1. *Systematic literature review process steps*

Distinctive of a high-quality literature review is its ability to demonstrate appropriate scope of the study, robustness in methodology, and clarity in its dissemination of the findings (Hart 1998; Levy and Ellis 2006). This is achieved through the structured and systematic review process, which forms the methodological framework of the literature review. For the study presented in this paper, a review process inspired by multiple sources has been applied. The overall structure of the process is inspired by the common three-step process described by multiple authors (e.g. Kitchenham 2004; Tranfield, Denyer, and Smart 2003) and includes the phases of planning the review, conducting the review, and reporting and dissemination of findings. Figure B1 visualises the methodology described above as applied in this literature review.

[Figure 1 about here.]

Phase one in Figure B1 covers an initial scoping study performed to determine the size, relevance, and delimitation of the subject area (Tranfield, Denyer, and Smart 2003). To ensure consistency and rigour in the review process, a review protocol, inspired by the PRISMA-P protocol (Moher et al. 2015) was developed.

Based on the scoping study, a keyword identification process initiated Phase two in Figure B1 resulting in the construction of search strings, selection of search engines and definition of exclusion and inclusion criteria as described in the following sections.

2.2. *Search Terms*

The purpose of the systematic review is to uncover all literature relevant to the research questions posed and the selection of keywords thus has implications on the scope of the literature search (Snyder 2019). Keywords were identified from seminal works (Levy and Ellis 2006) within the topics of platform-based product development (notably Simpson, Siddique, and Jiao 2006; Meyer and Lehnerd 1997; Ulrich, Eppinger, and Yang 2020) and process industry characteristics (notably King et al. 2008; Abdulmalek, Rajgopal, and Needy 2006) combined with discussions among the authors (Tranfield, Denyer, and Smart 2003). Search strings were constructed and tested in an iterative process adjusting for false positives and review scope. For example, 'paper' was originally included in reference to the process industrial product but returned mostly results referencing the written publication. The resulting final search string used was:

> product **NEAR/3** (portfolio **OR** family **OR** platform **OR** architecture **OR** commonality **OR** modularity **OR** module **OR** variety **OR** parametric **OR** configurable) **AND** (design **OR** development **OR** methodology **OR** approach **OR** management) **AND** ('process industry' **OR** 'process industries' **OR** glass **OR** ceramic **OR** cosmetics **OR** dairy **OR** film **OR** paint **OR** plastic **OR** pharmaceuticals **OR** stone **OR** clay **OR** steel **OR** metal **OR** chemical **OR** food **OR** beverage **OR** textile **OR** lumber **OR** wood **OR** pulp)

Additionally, the subject areas delimited to were engineering, design, development, management and innovation, and economics. See Appendix A for search engine-specific search string variations and databases.

2.3. *Resources Searched*

In addition to selection of appropriate keywords, the choice of academic search engines to use can have an impact on the results returned. A structured approach to search engine selection based on the findings of Gusenbauer (2019) has been employed. From this, four search engines met the criteria established (high volume of publications and proximity operators available): ProQuest, Web of Science, EBSCOhost and Scopus. Functional differences among the search engines prevented complete replication of search parameters as detailed in Appendix A.

2.4. *Document selection criteria and selection process*

Selection of literature was performed in a two-stage process. The first stage searched the selected academic search engines using the final search string. Following this, variants of forwards and backwards searching was performed on a delimited set of publications resulting from the first stage. Both literature searches were subject to the same selection criteria. Publication inclusion and exclusion criteria were divided into two types: bibliographical and topical criteria. The bibliographical criteria were applied as filters prior to executing the search in the academic search engines and the topical criteria were applied during screening of the individual publications. Bibliographical criteria included two common search query filters applied across the academic search engines: An English language filter and a full-text access filter. No publication period filters were applied. Topical criteria revolved around the relevance of the publications to the scope of the review. This process was guided by two inclusion criteria: direct references (e.g. designing a common platform, product architecture or modular products) and indirect references (e.g. complexity management techniques facilitating increased product variety or case studies from the process industry). A single exclusion criteria related to the explicit exclusion of process industry manufacturing equipment design was applied. The selection criteria are detailed in Appendix B.

Document selection was performed based on a three-step approach, in accordance with the inclusion and exclusion criteria defined. The approach screened the identified publications in progressively increasing detail to determine their relevance to this review. Following each step outlined in Figure B2, all publications considered outside the scope of this study were excluded from further consideration. Figure B2 briefly describes the content of each of the three steps as well as documents the publication selection progression for both stages of the literature search.

[Figure 2 about here.]

As is evident from Figure B2, most included studies, 53 percent, were identified during the block search and screening in Phase 1. Almost as many studies, 47 percent, were identified during the forwards and backwards search of Phase 2.

3. Bibliometric analysis

This section presents bibliometric analyses of the 62 publications selected for this study. The analyses cover different bibliometrics including publication trend, outlets and types.

Figure B3 shows the publication trend for the papers included in this study. The publications cover the period from 1984 to 2020, with most of the research (56,5 percent) being published after 2013. This seem logical as platform-based product development in general was popularised in the late 1990s by Meyer and Lehnerd (1997). Additionally, it was not until the 1980s that the natural modularity of chemical compounds was described (Kittleson, Wu, and Anderson 2012), paving the way for chemical product development based on combinations of multiple modules. Despite relatively few publications identified in total, the publication rate over the analysed period indicates a steadily increasing interest in the subject.

[Figure 3 about here.]

In total, 48 different publication outlets were included in this study, of which only the seven shown in Figure B4 had more than one publication. The most frequently appearing publication outlet is the journal Metabolic Engineering with 9,7 percent of all publications. Indeed, the majority of the most frequent publication outlets are chemical engineering focused journals with the remaining two journals being production and management related, respectively.

[Figure 4 about here.]

Figure B5 provides an overview of the different types of publication outlets included. The vast majority of publications are published in journals, indicating a relatively higher quality of research. Also evident from Figure B5 is the scarcity of trade journals, books, and other, more practitioner-oriented publication outlets. This could indicate that platform-based product development for non-assembled products is still an immature research field from an industry perspective.

[Figure 5 about here.]

The distribution of publications by content type is divided between original research articles and review articles. Here, almost 76 percent of the publications are categorised as original research articles, with reviews accounting for just over 24 percent. It is notable that of the 15 reviews all but two are published in chemistry-oriented journals, while the remaining two are published in technology and management (Bae and May-Plumlee 2005) and production engineering-oriented (McIntosh et al. 2010) journals.

4. Definitions of key concepts related to platform-based product development

This section presents identified definitions of fundamental concepts related to platform-based product development, as introduced in Section 1, focusing in particular on product architectures, modules and interfaces, platforms, and product families.

4.1. *Product architectures*

The *product architecture* is the foundation of any product platform as it reflects the relations between all functional elements of a product and their associated physical building blocks (Ulrich, Eppinger, and Yang 2020). In one of the earlier works on platform-based product development in the process industry, Meyer and Dalal (2002) define the product architecture simply as ‘the shared subsystems and interfaces’. While this definition is shared by Siiskonen, Folestad, and Malmqvist (2018), they further expand it to include components as well as the independency of individual modules, while also recognising the interrelatedness of components in terms of overall system performance. Ronaldo (2020) proposes a definition for a modular product architecture similar to that of Siiskonen, Folestad, and Malmqvist (2018) while emphasising the use of ‘standardised component boundaries [. . .] to achieve a loose combination [between modules]’, thereby emphasising the role of interfaces in product architectures. Despite the apparent similarity of the identified definitions to the traditional perspective on product architecture, there is an apparent lack of attention towards the function/module mapping of product architectures, as this aspect is not directly included in any of the definitions identified.

4.2. *Modules and interfaces*

Modules can be physical or non-physical entities and typically seek to attain some degree of functional purity (Ulrich, Eppinger, and Yang 2020) and assist in achieving expected system performance through governing *interfaces*. In the literature analysed, we have identified two major perspectives on modules within the context of the process industry. The first perspective relates to describing modules as collections of biochemical or chemical reaction elements that perform a related action (see e.g. Liu et al. 2018; Jeschek, Gerngross, and Panke 2017; Zargar et al. 2018), such as biochemical synthesis (Boock, Gupta, and Prather 2015). This is, for example, formalised in the multivariate modular engineering method (Biggs et al. 2014) and variations thereof (Lu, Villada, and Lee 2019). Regardless of the specific definition or description adopted, modules in the context of process industry products are still conceptualised similar to the traditional definitions with their focus on breaking down complex systems into manageable collections while attaining functional purity. Besides usage of the term module, the term ‘building block’ was adopted as a synonym in several studies (see e.g. Zhou et al. 2018; Faveere et al. 2020; Kühle, Teischinger, and Gronalt 2019). The second perspective identified is related to the similarities of the entities comprising a module, such as grouping based on food nutritional groups (Ortuño and

Padilla 2017), enzyme turnovers (Yadav et al. 2012) or active sites (McDaniel et al. 1997; Bedford et al. 1996). Despite most module descriptions focusing on non-physical elements such as reaction networks, some studies describe modules as physical entities. Examples include modules for 'filling purposes' which comprising a physical dose of a pharmaceutical product (Siiskonen, Folestad, and Malmqvist 2018) or modules being individual components of wood products (Kühle, Teischinger, and Gronalt 2019). In relation to interfaces in the context of process industry products, no explicit definitions have been identified. Of the studies that mention interfaces, some repeated the descriptions from discrete industry (Meyer and Dalal 2002; Kühle, Teischinger, and Gronalt 2019) yet did not elaborate on the application in the process industry or in the case of Siiskonen, Folestad, and Malmqvist (2018) illustrated the use only for physically assembled products. Others even argue that the concept is invalid in the process industry (Lager 2017).

4.3. *Platforms*

Simpson, Siddique, and Jiao (2006) note that various definitions of *product platforms* are provided in literature ranging from very broad perspectives on what constitutes a platform to very narrow and sometimes industry specific definitions. A widely used definition of product platforms was proposed by Meyer and Lehnerd in their seminal book from 1997. They define a product platform as 'a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced.' Table B2 lists the identified product platform definitions.

[Table 2 about here.]

The six definitions presented in Table B2 consider product platforms similar to traditional literature on the subject. The product platform concept is, therefore, also linked to product variety generation from common assets in the process industry. Besides definitions of product platforms, several other platform definitions were identified among the included studies. The production platform was defined by Lager (2017), as the unity of the product platform, process platform and raw material platform (for which they also provided definitions). Specific to chemical production, Liu et al. (2018) described a production platform as consisting of microbial cell factories. Besides product and production platforms, Dadfar et al. (2013) present a definition for technology platforms, which takes an integrated perspective of ‘capabilities, physical aspects and know-how’ as enablers of delivering product variety. Finally, both explicit (Lager 2017) and implicit (Sandberg and Larsson 2006; Karayel and Ozkan 2006; Xie et al. 2001) descriptions of knowledge platforms were identified, all to support new product development process by reusing design knowledge. In summary, regardless of the type of platform or the origin of the definition, platforms are considered as means of facilitating high product variety for manufacturers in the process industry. This is in line with the traditional platform perspective adopted in discrete manufacturing industry.

4.4. *Families*

Building on the common assets of a product platform is one or more *product families*, which are groups of related products (Simpson, Siddique, and Jiao 2006). The concept of both product families and process families are addressed among the identified studies. Lager (2017) presents a definition of a process family while two alternative definitions of product families, termed homogeneous and heterogeneous product families, are introduced by Alizon, Shooter, and Simpson (2010).

5. Drivers of Platform-based Product Development

This section presents an analysis of the drivers of platform-based product development. The studies are categorised after the primary drivers behind adopting platform-based product development approaches in manufacturing industry as presented by Muffatto (1999):

- Cost reduction
- Productivity of product development
- Development lead time reduction

For this categorisation, *cost reduction* refers broadly to reduced expenditures across the company's value chain. This includes, for example, lowered costs of manufacturing (e.g. reduction in variable costs or capital expenditures), product development (e.g. reduced need for testing or fewer man-hours spent on development of individual products), purchasing (e.g. fewer resources spent on certifying suppliers) or sales (e.g. fewer resources spent preparing product offers). *Productivity of product development* is more narrowly defined and refers to an increase in the capacity of new product development teams without supplying additional resources. Finally, *development lead time reduction* refers to the reduced duration of individual product development projects as facilitated by platform-based product development methods.

Based on the above-listed driver categories, grouping of the identified papers has been made and the results are summarised in Figure B6. It is acknowledged that there may be multiple drivers for a study, for which reason the figure includes overlapping regions visualised by the striped areas.

[Figure 6 about here.]

The findings related to each driver category are elaborated in the following sections.

5.1. *Cost reduction*

With 57 percent of the studies being categorised with a focus on cost reduction, this driver is the most represented driver for platform-based product development. Several studies take a more general perspective on reductions in cost resulting from implementing platform-based product development methods (Cherubini et al. 2009; Chambost, McNutt, and Stuart 2008), with multiple studies referring to aspects identical to those reported for discrete manufacturing industries (Lager 2017; Alizon, Shooter, and Simpson 2010; McIntosh et al. 2010; Meyer and Dalal 2002). A major theme concerning cost reduction is the increase of product yield through various modularisation techniques. This is mostly in reference to transitioning from fossil-based fuels to cost-efficient biofuels (Zargar et al. 2018; Guo et al. 2014; Sheppard et al. 2014; Xu et al. 2013; Zhang et al. 2018) and increasing supply of cost-efficient specialty chemicals (Zargar et al. 2018; Liu et al. 2018; Zhang et al. 2018; Ajikumar et al. 2010) as well as commodity chemicals (Becker et al. 2015). Besides these aspects, included studies also consider reduced product development costs in food (Bech et al. 2019) and pharmaceutical industry (Lu, Villada, and Lee 2019; Jeschek, Gerngross, and Panke 2017) as well as general production cost reductions (Siiskonen, Malmqvist, and Folestad 2020; Siiskonen, Folestad, and Malmqvist 2018; Layton and Trinh 2014; Mascal 2019). From a supply chain perspective, reductions in distribution costs (Sheppard, Kunjapur, and Prather 2016) and quality-related (Aeknarajindawat and Chancharoen 2019) or efficiency-related costs (Ronaldo 2020) are considered. Lastly, Siiskonen et al. (2019) consider cost reduction from a broader perspective through comprehensive evaluation of the product's impact on multiple dimensions including societal and environmental aspects.

5.2. *Productivity of product development*

The second most frequently represented driver category is concerned with increasing productivity of new product development and counts 55 percent of the included studies. Within this category, focus on delivering derivative products perform product innovation more efficiently have been identified as the two main perspectives. In relation to efficient development of derivative products, multiple studies approach this ability from a strategic perspective with references to studies citing benefits received in discrete manufacturing industry (see e.g. Lager 2017; Alizon, Shooter, and Simpson 2010; Van Kampen and Van Donk 2014; McIntosh et al. 2010; Bae and May-Plumlee 2005; Meyer and Dalal 2002), while others are concerned with specific industries such as forest biorefineries (Cherubini et al. 2009; Chambost, McNutt, and Stuart 2008) or pharmaceuticals (Siiskonen, Malmqvist, and Folestad 2020; Dadfar et al. 2013; Siiskonen, Folestad, and Malmqvist 2018; Govender et al. 2020; Norman et al. 2017). Several studies focus on how families of products may be efficiently created from common elements for product categories such as biofuels and specialty chemicals (Zargar et al. 2018; Yadav et al. 2012; Tseng and Prathera 2012; Pang et al. 2019), pharmaceuticals (Bedford et al. 1996; Ajikumar et al. 2010; De Almeida and De Moraes 2015; Hwang et al. 2020), glass wares (Chen and Wang 2000) or food (Ortuño and Padilla 2017). Studies focusing on more productive product innovation likewise approach the subject in different ways. Some consider platforms a means of reducing complexity in product development to reduce efforts required in development of new products (Kittleson, Wu, and Anderson 2012; Papin, Reed, and Palsson 2004; Kühle, Teischinger, and Gronalt 2019).

5.3. *Development lead time reduction*

The least represented driver is reduced product development lead time, which includes 47 percent of the studies. Besides studies mentioning reduced product development time in general as a driver of platform-based approaches (Bae and May-Plumlee 2005; Dadfar et al. 2013; Liu et al. 2018; Mounier and Baron 2012), two additional perspectives on product development lead time reduction was identified: reduced product testing time during development and increased integration of organisational functions involved in product development. A single study takes outset in a desire to reduce manufacturing maturation time (Bech et al. 2019) while the majority seek to specifically reduce iterative testing efforts required to achieve a product with the desired yield (Biggs et al. 2014; Boock, Gupta, and Prather 2015; Lu, Villada, and Lee 2019; Jeschek, Gerngross, and Panke 2017; Zhou et al. 2018; Temme et al. 2012; Garcia and Trinh 2019). Integration of organisational functions has been addressed by multiple authors. Most of the papers identified in this cluster are related to sheet metal processing (Sandberg and Larsson 2006; Karayel and Ozkan 2006; Xie et al. 2001; Chin and Tang 2002), and seek to decrease product development time by better integrating knowledge of product engineers and manufacturing engineers.

6. Approaches and Methods for Platform-based Product Development

The analysis of the platform-based product development methods identified in the included studies is inspired by the 12 fundamental concepts and their associated approaches described by Pirmoradi, Wang, and Simpson (2014). The concepts are grouped into the three categories of front-end issues, design and development issues, and back-end issues which are elaborated on in the following sections.

6.1. *Front-end Issues*

6.1.1. Product Architecture

Product architecture definition, i.e. describing components, functions and interfaces in a product structure, is a fundamental activity in platform-based product development. The primary studies concerned with this subject are:

- Focusing on non-assembled product types (photosensitive film and integrated electronic circuits), Meyer and Dalal (2002) define their product platform architecture and investigate their evolution and performance.
- Papin, Reed, and Palsson (2004) provides an abstraction of modularity on multiple hierarchical levels in biochemical networks, from the smallest components and their successive assembly into larger modules, consequently forming modular networks.
- Inspired by electronic circuitry design, Temme et al. (2012) proposes a concept for control and modularisation of biochemical pathways.
- Siiskonen, Folestad, and Malmqvist (2018) adopts the configurable component methodology (CCM) utilising function-means trees for definition of product and production architectures in pharmaceutical industry.

As the size and complexity of pathways increase, it becomes increasingly difficult to individually test and verify the functioning of the system elements (Temme et al. 2012) and decomposition of these systems into their functional elements is necessary to facilitate increased understanding of their interactions (Papin, Reed, and Palsson 2004). Thus, a key advantage of the proposed method by Temme et al. (2012) is the application of modularity to enable module-level testing prior to assembly into larger more complex systems. Much the same as how modularity in discrete manufacturing allows quality inspection and verification of individual modules prior to final assembly. Meyer and Dalal (2002) likewise discusses modular architectures in the context of process industry products, while arguing that the rigidity of process industries caused by high capital outlays can cause a dominant product architecture to impose further inertia rather than foster innovation and growth. Another link to products in assembled manufacturing industry is provided by the application of CCM as it originates from this industry and is applied in the context of personalised pharmaceutical products without modification to the fundamental methodology. However, the approach to modularisation diverges from discrete products, as the number of modules is parametric rather than the size or scale of these, as is typical in assembled products. Simulations performed support the conceptual approach of modular products as enablers of personalised medicine. (Siiskonen, Folestad, and Malmqvist 2018) Despite their focus on modularity and module hierarchies, Papin, Reed, and Palsson (2004) refrains from elaborating on module interface definitions, which is an important element in the establishment of modular product architectures. They note that although modularisation is applied in both mechanical and biological systems, the latter differs from engineered physical systems as the conceptual definition of modules can neglect complete network interaction and function.

6.1.2. Product Family and Platform Configuration

Attempting to better link business and engineering in platform-based product design, Alizon, Shooter, and Simpson (2010) addresses *product family and platform configuration.* Their study focuses on identifying leveraging strategies for product families based on functional similarity of derivative products and identifying the platform to build the product family around. They take outset in the original leveraging strategies proposed by Meyer and Lehnerd (1997) and proposes a fourth hybrid leveraging strategy. They demonstrate their methodology on both assembled products (power tools, consumer electronics) and non-assembled products (clothing) without distinction.

6.1.3. Product Family Modelling and Knowledge-based Systems

Related to the issue of *product family modelling and knowledge-based systems*, Cherubini et al. (2009) adopt a schematic approach based on four parameters (platforms, products, feedstock, and processes) for classification of biorefineries. In this scheme platforms are most important as they are the primary determinants of the range of products producible in the biorefinery (Cherubini et al. 2009). The schematic representation includes the combinatorial design space of biorefinery systems, and by extension the potential product range, according to identified pathways and can thus be considered a means of knowledge integration of the four parameters. The classification scheme is simple and graphically based, which provides for easy decision making with few variants, but as the number of biorefinery types increases the complexity of identifying the optimal design increases.

6.1.4. Product Portfolio Positioning

Product portfolio positioning is concerned with identifying the appropriate product mix to offer customers. The main studies on this subject are listed in Table B3.

[Table 3 about here.]

Krishnan and Zhu (2006) poses that further research should address horizontally differentiated markets as well the combination of both types of differentiation, which would align well with the hybrid leveraging strategy proposed by Alizon, Shooter, and Simpson (2010). While it appears that there is no fundamental difference in portfolio design between assembled and non-assembled products, the issue is argued to be computationally more complex for certain process industrial products (Adler, Smith, and Dumont 2010). The method proposed by Janssen, Chambost, and Stuart (2010) would be computationally less challenging to solve once the parameters are provided, yet quantification of environmental and social aspects were found to be particularly challenging. Furthermore, despite co- and by-products being prevalent in biorefineries it is a topic not addressed in their decision model. Even so, it is expected that the methodology could be adapted to include these.

6.2. *Design and Development Issues*

6.2.1. Product, production, and other platforms

Design and development of *platforms* is about determining which elements to standardise and which can be varied to suit different needs. The major studies concerned with platform development are presented in Table B4.

[Table 4 about here.]

Concerning the generic methodology presented for platform design in the process industry, Lager (2017) argues that multiple-progression QFD is favourable in process industry contexts due to the method being simpler to apply for homogeneous products. In general, considering both processes and products during platform design is argued as imperative for process industry products (see e.g. Lager (2017); Siiskonen, Malmqvist, and Folestad (2020); Meyer and Dalal (2002)). This is central to the approach employed by Siiskonen, Malmqvist, and Folestad (2020), who implements early stage evaluation of platform designs to assist to mitigate risk in pharmaceutical development projects as these are often characterised by high investments and long planning horizons (De Almeida and De Moraes 2015). Despite Lager (2017) arguing against adopting traditional platform perspectives (i.e. comprised of architectures with modules and defined interfaces), multiple studies develop platforms based on interacting modules (see e.g. (Zhang et al. 2018; Tseng and Prathera 2012; Siiskonen, Malmqvist, and Folestad 2020)) and appears to adhere to functionally pure modules (Layton and Trinh 2014; Sheppard, Kunjapur, and Prather 2016). Zhang et al. (2018) find that there is a positive relation between the number of modules in a pathway and its potential performance, yet recognises that this implies a complexity trade-off when optimising pathways. Furthermore, they find that modularisation: allows for decoupling of pathway elements, thereby limiting propagation of negative effects across modules; simplifies pathway engineering, as pathway construction and optimisation can be separated; and facilitates ‘plug-n-play’ pathway modification to produce new products.

6.2.2. Variety versus commonality

In product design and development, one of the key issues is the determination of the *variety versus commonality* trade-off. Atkins, Granot, and Raghavendra (1984) develop a non-linear integer programming model to optimise the variety of product variants against the production efficiency of a plywood manufacturer. A challenge experienced by plywood manufacturers is the varying grade of the raw material (wood logs) received, which impacts production waste (Atkins, Granot, and Raghavendra 1984). Even so this aspect is not included in the model. While quantitative models presumably also lie at the foundation of the decisions made, Chambost, McNutt, and

Stuart (2008) describe the challenge from a more general perspective. They propose a three-phase implementation framework focusing on leveraging the biorefinery product portfolio into existing operations by reducing operating costs, increasing revenues, and improving margins. Platform-based approaches relying on diverse product portfolios are seen as critical to risk management in the rapidly developing bio-based industry, as volatility of individual products can be significant (Chambost, McNutt, and Stuart 2008).

6.2.3. Design optimisation

Within the field of chemical engineering and product design, *design optimisation* facilitated by modular product design appears to be a major theme among the included studies. Ajikumar et al. (2010) introduces the concept of 'multivariate modular pathway engineering' (later rephrased into 'multivariate modular metabolic engineering' (MMME) by Yadav et al. (2012)), in which pathways are divided into modules, which allows for combinatorial searching of smaller solution spaces to identify optimal pathway configurations. They then apply pathway modularisation to a taxadiene-producing pathway, resulting in a two-module configuration (Ajikumar et al. 2010). Biggs et al. (2014) review the concept of MMME and illustrate the method by a three-step approach consisting of pathway modularisation, module construction, and searching of the solution space to identify high productivity strains. Strategies are then proposed for modularising pathways based on chemical parameters such as identified clusters of comparably performing enzymes or specific changes in the pathway biochemistry (Biggs et al. 2014). Recognising the need for a systematic framework for modular product development in biochemistry, Yadav et al. (2012) proposes a framework based on the pathway modularisation and optimisation approach developed by Ajikumar et al. (2010). Boock, Gupta, and Prather (2015) review the application of screens and modular design for pathway optimisation in metabolic engineering. Their representation of modular design takes outset in a defined pathway architecture and mapping of enzyme functions as inputs to developing a modular design. Based on the modular design, product designers may then construct pathways from these modules and, in conjunction with high throughput screens eliminate performance limiting elements along the pathway (Boock, Gupta, and Prather 2015). Cao et al. (2016) and Xu et al. (2013) likewise utilises modularity for the purpose of pathway optimisation. While the former study presents a five-module pathway, where the individual modules are adjusted to optimise production of gasoline-range alkanes (Cao et al. 2016), the latter synthesises other fatty acids as petroleum fuel substitutes through a three-module pathway (Xu et al. 2013). Both studies utilise a multivariate approach to tune individual modules towards a global optimum in terms of pathway productivity. Another review which concerns itself with product design optimisation is Jeschek, Gerngross, and Panke (2017) who focuses on multivariate methods for optimisation of pathway productivity. Using a library containing essential pathway elements categorised by function, complete pathways are assembled from these individual modules using various strategies as a means of identifying an optimal pathway design (Jeschek, Gerngross, and Panke 2017). Based on an existing method for generation of standardised pathways and pathway elements, Zhou et al. (2018) propose the inclusion of machine learning algorithms to facilitate combinatorial searching to optimise product designs. Based on the combination of a chemical platform and Design of Experiments, Meador et al. (2008) demonstrate development of a family of film products. Through multiple steps, DoE is employed to select the most promising product candidates based on their performance (Meador et al. 2008). While focus is stated to be on demonstrating the development of a family of products, the study seems to be mostly concerned with design optimisation from a chemical engineering perspective. Ortuño and Padilla (2017) likewise focus on design optimisation. However, whereas the above-described studies focus on optimisation of a single product, Ortuño and Padilla (2017) seeks to optimise multiple customised products against specific consumer preferences. This is achieved through the development of an optimisation model based on a combination of fuzzy logic and mixed integer linear programming (Ortuño and Padilla 2017). The customisation of products according to individual customer needs is facilitated by a defined product platform of food products and the utilisation of a standardised packaging.

6.2.4. Design Support Systems

Design support systems (DSS) are information repositories enabling product designers to reuse existing knowledge to efficiently create derivate products. Several examples have been identified in literature and Table B5 lists the relevant publications on this subject.

[Table 5 about here.]

The identified sheet metal forming DSSs appear of more practical relevance than the DSS for chemical products due to a narrow perspective on product design, thereby omitting many elements of designing an economically feasible product. It is questionable if the DSS developed by Chen and Wang (2000) would apply equally well to non-assembled products that are difficult to visualise for non-professional designers. The inclusion of production processes and their impact on the product design is an essential aspect to incorporate in DSSs for the process industry, as is done in several of the stamped metal parts cases yet is missing from the chemical products case. A potential issue of DSSs in the process industry is related to the ability to codify the design knowledge, which is deemed impossible in the case of some chemical products (Eng et al. 2018).

6.3. ***Back-end Issues***

6.3.1. Manufacturability

Utilising a multi-step QFD-based approach, Kühle, Teischinger, and Gronalt (2019) addresses the issue of *manufacturability* through a conceptual framework based on propagating requirements inherited from the finished product through product modules onto the manufacturing processes and technology. Acquiring a holistic perspective on manufacturability is argued as imperative for the competitiveness of the SMEs that comprises the wood products sector studied. The similarity of the method with that proposed by Lager (2017), could indicate a potential for using the method to establish production platforms to efficiently support the product variants considered.

6.3.2. Metrics and indices

Related to the operational impacts of product design, *metrics and indices* provides insight into the quantitative effects of adopting platform-based development strategies. Table B6 summarises the metrics and indices identified.

[Table 6 about here.]

Meyer and Dalal (2002) adapted the Platform efficiency measure from Meyer, Tertzakian, and Utterback (1997) to the process industry by explicitly including capital and manufacturing engineering costs as these often present significant investments. Besides facilitating selection of a product family leveraging strategy, the HHR metric also provides insight regarding the need for product differentiation across dimensions other than function, such as aesthetics (Alizon, Shooter, and Simpson 2010). In a study on the innovation capability of pharmaceutical SMEs, Dadfar et al. (2013) measured five ‘innovation enablers’ as indicators of product and technology platform leverage for product innovation. While Meyer and Dalal (2002) and Dadfar et al. (2013) focus on the financial performance of companies as a result of their leveraging of platform principles, Alizon, Shooter, and Simpson (2010) and Siiskonen, Malmqvist, and Folestad (2020) takes a predominantly market-centric perspective on the same issue. Furthermore, both Meyer and Dalal (2002) and Alizon, Shooter, and Simpson (2010) proposes metrics that are to be evaluated on both product variant and product family level. While Siiskonen, Malmqvist, and Folestad (2020) does not explicitly make the same distinction, a product family-level quality decay metric may aid in identifying optimal product family design parameters.

6.3.3. Supply chain management

While both changes in product and production design are often necessary to accommodate platform-based product development, the surrounding supply chain must also be structured to accommodate this setup. Studying Asian supply chains in the food (Ronaldo 2020) and textile industries (Aeknarajindawat and Chancharoen 2019), both studies utilise hypothesis testing and industry-wide surveys and find positive relationships between individual company performance in the supply chain and the implementation of product modularity. Despite the sizeable populations surveyed, the magnitude of improvement related to utilisation of product modularity remains unclear.

6.3.4. Postponement

Delayed differentiation or *postponement* as it is also referred to is a commonly applied practice in discrete manufacturing industry enabled by modularisation and often associated with platform-based product development. Several studies addressing postponement in a process industry context have been identified. Their major contributions are summarised below:

- McIntosh et al. (2010) presents a comprehensive review on mass customisation in food industry with particular focus on how different variants of postponement may enable – or already have enabled – delayed differentiation in two dairies and a potato chips plant.
- Focusing specifically on form postponement in a dairy, Van Kampen and Van Donk (2014) analyses and simulates the performance impact of adopting the form postponement strategy compared to traditional batch processing.
- Bech et al. (2019) investigates challenges and potentials of process variety management in a pastry manufacturing company focuses in part on delaying customer differentiation by employing fewer standard doughs.

In general, most postponement examples identified in literature has been from the food industry and covers dairies (McIntosh et al. 2010; Van Kampen and Van Donk 2014; Lager 2017), snack manufacturers (McIntosh et al. 2010), bakeries (Bech et al. 2019) and breweries (Lager 2017). Indeed, of six postponement variants evaluated it was found that three were already being applied to some extent with the remaining three being potentially possible (McIntosh et al. 2010). However, despite the theoretical possibility for application the authors note potential practical issues related to the special characteristics of the process industry such as limited shelf life of semi-manufacturers, which is a challenge also noted by Bech et al. (2019). Despite these industry-specific challenges, modularisation and platform-based products are still proposed as the most relevant enabler of delayed differentiation. Besides examples from and beverage manufacturers, the potential for delayed differentiation in pharmaceutical manufacturing is briefly discussed by Siiskonen, Malmqvist, and Folestad (2020).

7. Discussion

7.1. *Definitions of key subject terms*

In Section 4, identified definitions related to key terms in platform-based product development was presented and three definitions of product architectures identified. Additionally, several studies present illustrations of product architectures (see e.g. Meyer and Dalal 2002; Siiskonen, Folestad, and Malmqvist 2018). Even so, there is generally a lack of the explicit consideration of this topic in relation to the development of the products presented. This appears to be a major gap in terms of advancing platform-based product development within the process industries as the definition of the product architecture is a fundamental step in any platform-based design of product families (Ulrich, Eppinger, and Yang 2020).

Additionally, while the specification of interfaces is a critical aspect in defining modular product architectures (Ulrich, Eppinger, and Yang 2020), no such definitions were identified among the included studies. This is despite several studies utilising modularity in product development and illustrating product architectures. Consequently, further research into the usage and instantiation of interfaces in product development in a process industrial context is considered relevant to further the application of platform-based product development in this industry sector.

Another interesting topic to explore further is the apparent disagreement concerning the suitability of adopting platform-related terms from discrete industry. While Lager (2017) argues that the characteristics of products in the process industry means that defining modules and interfaces is not possible, several studies of chemical and pharmaceutical product development exploiting modularity was found. The evident application of modularity in product development in the process industry therefore calls for further investigation into which circumstances modularity may be feasible in terms of process industrial products, as well as where it may not be.

7.2. *Drivers of platform-based product development*

Although Section 5 showed a nearly equal distribution between cost reduction and productivity of product development as overall drivers towards pursuing issues related to platform-based product development, the former often appears to take precedence. Consequently, the ability to deliver a high variety of industrially relevant products becomes a by-product rather than an integrated aspect of many studies. This appears to be particularly evident in the studies rooted in chemical engineering where increased yield, pathway efficiency or other cost related aspects are in focus. As Section 5 shows, several studies focus on development of bio-based alternatives to existing petroleum-based products, such as fuel. For these alternatives to be commercially viable, they must attain competitiveness with their petroleum-based counterparts (Sheppard, Kunjapur, and Prather 2016), which may provide some explanation to the results. Even so, other studies argue that engineered alternatives present the only feasible approach to meet growing market demands of naturally derived specialty chemicals, such as aromatic compounds used in cosmetics (Zhang et al. 2018). Regardless, focus seems to be centred around leveraging platform-based development for high performing individual products rather than to achieve high product variety.

7.3. *Methods and approaches for platform-based product development*

The differences in both product and process characteristics between process and discrete manufacturing industries together with the disagreement on the feasibility of adopting established concepts, may have given cause to believe that principles and methods may not have translated well across these industries. Nevertheless, the adoption of both terminologies and concepts by several studies and in particular the direct application of methods from the discrete industry for process industrial products suggests that this may be a feasible approach for companies seeking to adopt platform-based development in the process industry. However, while multiple studies (Siiskonen, Malmqvist, and Folestad 2020; Meyer and Dalal 2002) demonstrate the applicability of existing methods from discrete manufacturing industry, they do not present arguments for their choice of method nor for traits of the method that made such application possible. For example, Siiskonen, Folestad, and Malmqvist (2018); Siiskonen, Malmqvist, and Folestad (2020) do not focus on why the selected method is particularly well-suited for application in process industries or as an enabler of mass customisation of pharmaceutical products. Therefore, given the plethora of methods developed to support platform-based product development in discrete manufacturing industry (see e.g. Pirmoradi, Wang, and Simpson (2014)) such insight would enable both academics and practitioners in furthering knowledge and application of platform-based product development in process industries. As an extension of this, it is considered important for practitioners to know how specific process industry product characteristics impacts the ability to utilise existing methods, as several studies (Papin, Reed, and Palsson 2004; Siiskonen, Malmqvist, and Folestad 2020; Lager 2017) notes that some characteristics of process industry products may make application of platform-based development challenging.

This may be due to back-end and front-end issues being more similar across process and discrete industry or if the concept is still so novel that it is primarily a product engineering exercise. However, related to front-end issues Krishnan and Zhu (2006) showed that existing methods may not fair equally well for all process industry product types. Furthermore, Chambost, McNutt, and Stuart (2008) notes that taking a customer and market perspective on design of product portfolios - and by extensions the platforms to employ, was lacking in both literature and industry. However, this may also be attributed to the commodity nature of the products manufactured, causing companies to emphasise production efficiency and cost over product differentiation.

Despite multiple authors pressing the importance of considering both the product and process in process industries few studies addresses this (e.g. Lager 2017; Siiskonen, Malmqvist, and Folestad 2020; Siiskonen, Folestad, and Malmqvist 2018). As such, seeking inspiration in co-development (Michaelis 2013) principles, as proposed by Siiskonen, Malmqvist, and Folestad (2020), may prove interesting due to the general characteristics of the process industry.

Of the studies that do consider both aspects, there is a lack of case studies from industry demonstrating the feasibility of these approaches. In general, among the studies identified, the majority are focused on either proposing conceptual models or performing laboratory experiments. Demonstrating this aspect is, therefore, considered an important step towards furthering the expansion of platform-based product development in the process industries. This is based on the influence that industrial cases of platform-based product development and their results, such as the success stories of Black & Decker (Meyer and Lehnerd 1997) and Volkswagen (Simpson, Siddique, and Jiao 2006) have had in discrete manufacturing industry.

8. Managerial implications

From our study, the key managerial implications are first and foremost that platform-based product development is applicable to process industry products as well. While the amount of scientific literature addressing the topic is limited, there are several examples and cases of companies having adopted the approach. In addition to specific cases and examples, plenty of references and anecdotal evidence from industry applications of platform principles are identified. This leads us to believe that platform-based development principles are more common in the process industry than indicated by literature.

Having identified usage of traditional platform-related definitions in process industry literature in combination with demonstrated application of development methods originating in discrete manufacturing industry, there is relatively clear evidence that platform-based development principles can be used in the process industry. Furthermore, the relation to discrete industry definitions and methods leads us to suggest that platform-based development projects be based on either one of the identified methods from this study or a well-documented method from discrete manufacturing industry. The feasibility of using existing methods from discrete manufacturing industry may especially hold true for the front-end issues of platform-based development, which are considered more similar across discrete and process industry compared to design and development and back-end issues as is also demonstrated by the comparison of industry characteristics in Section 1.3 – here most identified differences relate to product or production characteristics rather than market characteristics.

It is our hope that the comprehensive review and inclusion of references to industrial examples and cases throughout can serve as a source of inspiration for managers and product developers considering applicability of platform-based development in the process industry or their specific industry sector.

9. Conclusion

Motivated by the lack of literature on platform-based product development issues in the process industry, this study has identified and reviewed existing literature on the subject. This has been achieved through a comprehensive systematic literature review as outlined in Section 2.

A bibliometric analysis of the 62 included studies was performed in Section 3, concluding that even though the total body of knowledge on the subject is relatively limited, there has been a nearly exponential growth in literature over the past two decades. Even so, the identified literature is published mostly within academic journals with very little knowledge disseminated through books, trade journals or similar more practice-oriented publication outlets.

Based on the overall research question of what motivates the pursuit of platform-based product development principles in process industries, three underlying aspects covering the specific definitions, drivers and approaches of platform-based product development in process industries formed the main synthesis part of the paper, as described in the following sections.

9.1. *RQ1: Definitions of key platform concepts in the process industry*

Analysing the use of subject relevant definitions, Section 4 showed that the product platform definitions identified shared significant similarity to those found in discrete manufacturing industry. Additionally, the analysis found that while modules and modularity was a relatively widespread concept in the literature identified, platforms and especially product architectures and interfaces as explicit concepts were sparse. Consequently, despite disagreements on the applicability of certain concepts within the context of the process industry, the identified body of literature and the several anecdotal examples identified presents demonstrates that there appears to be a potential in pursuing existing methodologies for platform-based development of process industry products.

9.2. *RQ2: Drivers of platform-based development in the process industry*

The drivers of pursuing platform-based product development principles were analysed in Section 5. Here it was found that cost reduction and productivity of product development were the two most frequently identified drivers, with development lead time reduction being the least emphasised driver category. In general, modularisation efforts were mostly aimed at cost reductions while the market perspective of being able to provide high product variety, in accordance with the general market trends described in Section 1, was often a minor consequence. This suggests that the current literature is heavily rooted in engineering with only limited ties to the market perspective.

9.3. *RQ3: Methods and approaches for platform-based development in the process industry*

Section 6 analysed approaches and methods for platform-based product development issues using an established framework. The analysis found that although studies were identified within all relevant categories, the distribution among them were uneven. Design and development related issues were represented significantly more than market related issues or manufacturing and supply chain issues. In particular, studies concerned with chemical platform design and design optimisation constituted a large share of the included studies. Analysing industrial platform cases and examples in the literature revealed that several studies included empirical evidence of platform-based products and even more studies presented anecdotes of this. Most frequent were cases and examples from the food, beverage, and electronics industry. It was also observed that despite the prevalence of chemistry-focused studies identified, there is a distinct lack of industrial cases and examples from this sector. Based on these findings, it appears that the application of formal platform-based product development in the process industry is still in a relatively immature state;, and that more research is needed to demonstrate both industrial implementation and associated business results.

10. Research agenda

Having performed an extensive systematic review of the relatively limited literature on platform-based product development in process industries, several aspects are identified as relevant to further advance the body of knowledge on the subject:

- Investigating product architecture design for the process industry appears to be a major gap in terms of advancing the concept within the process industries as the definition of the product architecture is a fundamental step in any platform-based design of product families (Ulrich, Eppinger, and Yang 2020), and only rudimentary discussions on this subject were identified.
- Further research into the usage and instantiation of interfaces in product development in a process industrial context is considered relevant to further the application of platform-based product development in this industry.
- The evident application of modularity in product development in the process industry calls for further investigation into which circumstances modularity may be feasible in terms of process industrial products, as well as where it may not be.
- Conducting further research into how high product variety, enabled by platform-based approaches, may be leveraged for chemical products from a market-oriented perspective is considered of relevance to further the application of platform-based product development in the process industry.
- Identifying what characteristics or parameters of a method makes it a candidate for application across industries is considered of relevance as it would aid both researchers and practitioners in furthering the application of platform-based product development in the process industries.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Rasmus Andersen, upon reasonable request.

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Appendix A. Search Strings and Database Selections for Selected Academic Search Engines

A.1. *ProQuest*

A.1.1. Search String

TI,AB,IF(product NEAR/3 (portfolio OR family OR platform OR architecture OR commonality OR modularity OR module OR variety OR parametric OR configurable) AND (design OR development OR methodology OR approach OR management) AND ("process industry" OR "process industries" OR glass OR ceramic OR stone OR clay OR steel OR metal OR chemical OR food OR beverage OR textile OR lumber

OR wood OR pulp OR dairy OR pharmaceutical)) AND la.exact(”English”) AND PEER(yes) AND SU(engineering OR design OR development OR management OR innovation OR economics)

A.1.2. Databases

ABI Inform Collection, Ebook Central, Materials Science Engineering Collection, ProQuest Dissertations & Theses Global, Research Library, Science Database, Technology Collection

A.2. *Web of Science*

A.2.1. Search String

TS=(product NEAR/3 (portfolio OR family OR platform OR architecture OR commonality OR modularity OR module OR variety OR parametric OR configurable) AND (design OR development OR methodology OR approach OR management) AND (”process industry” OR ”process industries” OR glass OR ceramic OR stone OR clay OR steel OR metal OR chemical OR food OR beverage OR textile OR lumber OR wood OR pulp OR dairy OR pharmaceutical)) AND SU=(engineering OR design OR development OR management OR innovation OR economics))

A.2.2. Databases

Science Citation Index Expanded, Conference Proceedings Citation Index, Emerging sources Citation Index

A.3. *EBSCOhost*

A.3.1. Search String

TI(product N3 (portfolio OR family OR platform OR architecture OR commonality OR modularity OR module OR variety OR parametric OR configurable) AND (design OR development OR methodology OR approach OR management) AND (”process industry” OR ”process industries” OR glass OR ceramic OR stone OR clay OR steel

OR metal OR chemical OR food OR beverage OR textile OR lumber OR wood OR pulp OR dairy OR pharmaceutical)) OR AB (product N3 (portfolio OR family OR platform OR architecture OR commonality OR modularity OR module OR variety OR parametric OR configurable) AND (design OR development OR methodology OR approach OR management) AND (”process industry” OR ”process industries” OR glass OR ceramic OR stone OR clay OR steel OR metal OR chemical OR food OR beverage OR textile OR lumber OR wood OR pulp OR dairy OR pharmaceutical)) AND SU(engineering OR design OR development OR management OR innovation OR economics)

A.3.2. Databases

Academic Search Premier, Business Source Premier, eBook Collection (EBSCOhost)

A.4. *Scopus*

A.4.1. Search String

TITLE-ABS-KEY(product W/3 (portfolio OR family OR platform OR architecture OR commonality OR modularity OR module OR variety OR parametric OR configurable) AND (design OR development OR methodology OR approach OR management) AND (glass OR ceramic OR stone OR clay OR steel OR metal OR chemical OR food OR beverage OR textile OR lumber OR wood OR pulp OR dairy OR pharmaceutical)) AND SUBJAREA(BUSI OR CENG OR ECON OR ENGI) AND (LIMIT-TO(LANGUAGE,”English”))

A.4.2. Databases

No database selection possible.

Appendix B. Literature selection criteria

The delimited set of publications resulting from the three-step approach outlined above was subjected to a relevance assessment inspired by the approach of Pittaway et al.

(2004), using an adapted three-category scale:

A) These papers focus explicitly on platform-based development issues in process industries (e.g. Lager 2017; Siiskonen, Malmqvist, and Folestad 2020).
B) These papers focus either directly or indirectly on platform-based development issues where the process industry context may be more or less important (e.g. Alizon, Shooter, and Simpson 2010; Atkins, Granot, and Raghavendra 1984).
C) These papers include aspects related to platform-based development issues to a lesser degree, which may be included as the context for the study (e.g. Van Kampen and Van Donk 2014; McIntosh et al. 2010).

In this study, 'A'-rated publications were defined as having high relevance, 'B'-rated publications moderate relevance and 'C'-rated papers minor relevance to the scope of this study.

Figure alt text

Figure B1. The methodology used for the systematic literature review from planning to reporting and dissemination of the review.

Figure B1 (Alt text). A process involving three steps arranged in sequence. Each step includes a number of activities, also sequentially structured, performed to complete the given step.

Figure B2. Three-step publication delimitation approach applied. The progression in number of publications excluded at each step is shown by the dotted lines.

Figure B2 (Alt text). The three main steps arranged in two blocks, each representing a specific phase of the literature review. The number of search results identified and analysed is represented as sequentially-linked steps with each step resulting in both a number of excluded results and a number of included results.

Figure B3. Publication trend of all publications included in the study from 1984 to 2020.

Figure B3 (Alt text). A line graph showing a general increase, despite large year-to-year variations in publication numbers.

Figure B4. Publication frequency by publication source for all outlets with at least two publications included in this study.

Figure B4 (Alt text). A vertical bar graph showing the number of publications for each of the seven most frequent publication outlets in the study sample.

Figure B5. Distribution of publications by publication source type.

Figure B5 (Alt text). A pie chart representing the number of studies included for each of the five publication types.

Figure B6. Distribution of drivers identified among the included studies. Drivers are shown by category including compound categories marked by the striped regions (CR = cost reduction, DR = development lead time reduction, PP = productivity of product development).

Figure B6 (Alt text). A pie chart showing the number of studies identified, which focuses on one or more of the investigated drivers for platforming. The chart includes three striped regions representing overlaps between two adjacent driver categories.

Table B1. A summary of major differentiating characteristics between process and discrete manufacturing industry products. These are generalised characteristics and not necessarily representative of all process industry products.

Characteristic	Process industry	Discrete industry	Description
Product structure	Shallow	Deep	Discrete products are typically comprised of multiple systems and subsystems, while continuous products are often comprised of few subsystems if any (King et al. 2008).
Product constellation	Blended formula	Assembled structure	Process industry products are often made by combining and mixing materials, whereas discrete products are assembled of components (Samuelsson, Storm, and Lager 2016; Frishammar, Lichtenthaler, and Kurkkio 2012).
Number of input materials	Few	Many	Products in the process industry are typically only comprised of few different raw materials, whereas discrete products are often made of many different materials (Abdulmalek, Rajgopal, and Needy 2006).
Storage time	Often limited	No practical limit	Limited shelf-life due to deteriorating products are frequently observed for process industry products (Flapper et al. 2002), whereas this is rarely the case for discrete industry products.
Material grade	Variable	Predictable	Utilisation of materials of natural origin in process industry products often imply varying quality, while components in discrete products are typically of more predictable quality (Flapper et al. 2002).
Regulatory constraints	Often experienced	Rarely experienced	Process industry products are influenced by government regulations more often than discrete products (Kohr, Budde, and Friedli 2017).
Product flow	Primarily divergent	Primarily convergent	While discrete products are often assembled from many subsystems, which are assembled of many parts, process industry products are typically separated into multiple derivative products (King et al. 2008; Lyons et al. 2013).
Balance of residual products	Important	Not important	In processing process industry products, co- or by-products are often made in varying conditions (Samuelsson, Storm, and Lager 2016), whereas this is not an issue for discrete products.

Table B2. Product platform definitions identified in selected studies.

Publication	Product platform definition
Cherubini et al. (2009)	‘[. . .] intermediates which link feedstocks and final products.’
Dadfar et al. (2013)	‘[. . .] a variety of products which are produced in the same technology platform but with new applications.’
Lager (2017)	‘[. . .] the common basis of all individual products within a product family; thus it is linked to that product family while it can serve multiple product lines in the market.’
McIntosh et al. (2010)	‘[. . .] architectural concepts, comprising interface definitions and key components, addressing a market and being a base for deriving different product families.’
Meyer and Dalal (2002)	‘[. . .] the common subsystems and interfaces used within and shared across different individual products.’
Zhang (2014)	‘[. . .] a combination of a set of modules and ports.’

Table B3. Studies identified concerning product portfolio positioning for process industry products.

Reference	Subject	Remarks
Krishnan and Zhu (2006)	Investigates the impact of development costs on product family-design decisions for development-intensive products (DIPs) such as pharmaceuticals.	• Finds that subsumed product design does not translate well to DIPs. • Focuses solely on vertically differentiated products.
Janssen, Chambost, and Stuart (2010)	Proposes a multi-criteria decision model using experts' preferences to evaluate biorefinery design alternatives.	• Extends product portfolio decisions to include environmental and societal impacts.
Adler, Smith, and Dumont (2010)	Product portfolio optimisation using discrete choice modelling for food and apparel products.	• Food and apparel products are typified by highly heterogeneous customer preferences. • Tested their models in real commercial settings, showing increased performance.

Table B4. Studies concerned with platform development and design.

References	Subject	Remarks
De Almeida and De Moraes (2015)	Proposes multiphase framework for technology and innovation platform design for pharmaceutical products.	• Involves broad array of stakeholders in platform development.
Lager (2017)	QFD-based framework integrating raw material, product, and process platforms for design of non-assembled products into a combined production platform.	• Includes integrated knowledge platform to support future development. • Adopts alternative platform definitions.
Siiskonen, Malmqvist, and Folestad (2020)	Proposes two-stage methodology for platform development in pharmaceutical industry comprising platform preparation and platform execution.	• Extends previous work by Siiskonen, Folestad, and Malmqvist (2018). • Simulations argue against modular product architecture.
Layton and Trinh (2014); Zhang et al. (2018)	Utilises modular metabolic engineering method to design modular pathways and define platform elements.	• Variant products possible by changing final module in pathway. • Modularisation enables efficient access to vast design space.
Tseng and Prathera (2012); Zargar et al. (2018)	Platforms enabling development and production of multiple bioproducts based on three-module architecture.	• Implements scalable modules for carbon chain extension. • Modular design limited by insufficient architecture knowledge Zargar et al. (2018)
Sheppard et al. (2014); Sheppard, Kunjapur, and Prather (2016)	Applies retro-biosynthesis (reverse pathway construction) on modularised pathway to identify feasible platform variants.	• Architecture capable of producing alternative products with same pathway or vice versa. (Sheppard et al. 2014) • Scalable platform enables tuning of product output distribution. (Sheppard, Kunjapur, and Prather 2016)
Mascal (2019)	Proposes non-modular platform for development of diverse biobased product families.	• Platform is argued as industrially and commercially relevant.

Table B5. Primary studies related to design support systems.

Reference	Subject	Remarks
Chen and Wang (2000)	Glassware product customisation for non-professional designers.	• Fuzzy-logic allows usage of natural language specification.
Xie et al. (2001)	Platform for collaborative concurrent sheet metal product development.	• Relies on case-based reasoning to support design process. • Modular system design allows for adaption to other product types.
Chin and Tang (2002)	Web-based product design platform for stamped sheet metal parts.	• Potential for further integration of machine learning to support design process.
Karayel and Ozkan (2006)	Agent-based product design system for sheet metal parts.	• Implements artificial intelligence to support design process. • Modular system allows tailoring to specific product groups.
Sandberg and Larsson (2006)	System for automated redesign of sheet metal parts.	• Implements both case-based reasoning and knowledge-based engineering to achieve better part designs. • Only paper to present industrial application of system.
Eng et al. (2018)	Design toolkit for module identification in chemical product design.	• The toolkit is part of a three-step design paradigm.

Table B6. Primary studies concerned with metrics and indices.

Reference	Subject	Measures	Remarks
Meyer and Dalal (2002)	Development decisions' effect on platform efficiency and relationship between platform reuse and product family performance.	• Platform efficiency (E) • Reuse (U)	• Measures can be applied on product variant and product family level. • Provides method for alternative reuse measure based on subjective input.
Alizon, Shooter, and Simpson (2010)	Selection of platform leveraging strategy based on product functional commonality.	• Homogeneity-Heterogeneity ratio (HHR)	• Applied on both function and product family level.
Siiskonen, Malmqvist, and Folestad (2020)	Concurrent product and manufacturing platform design based on customer benefit and cost-benefit trade-off.	• Quality decay (Q) • Utility (U)	• Simplified evaluation model shows preference against modular product design.

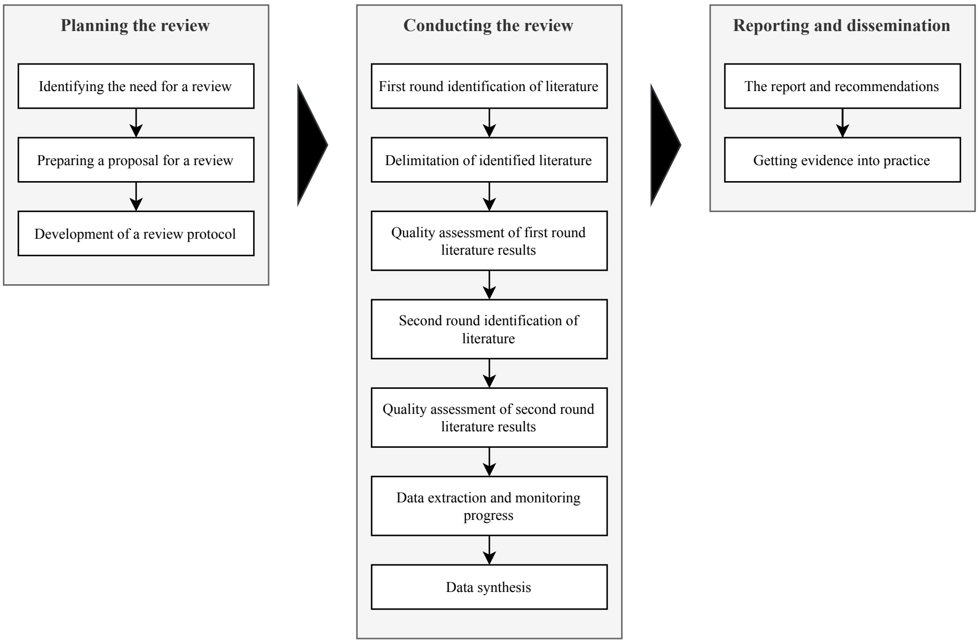

Figure B1. The methodology used for the systematic literature review from planning to reporting and dissemination of the review.

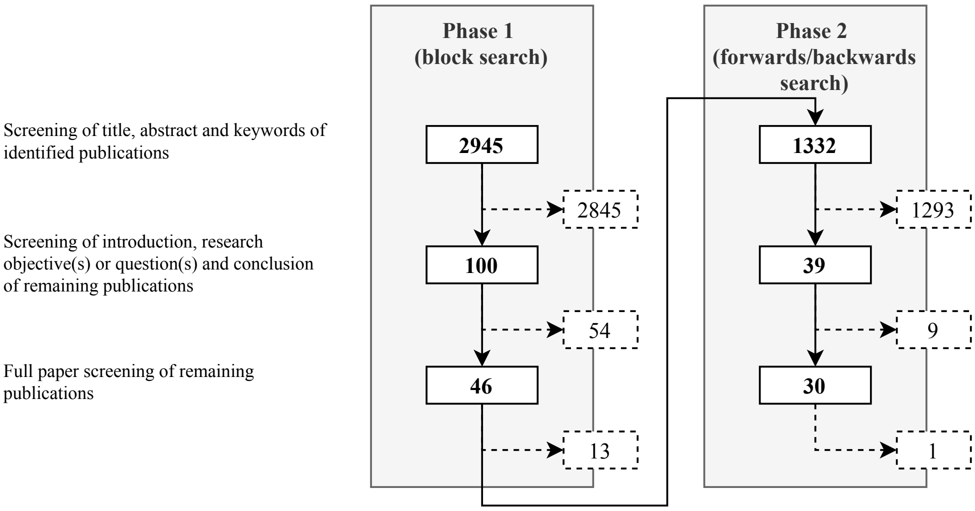

Figure B2. Three-step publication delimitation approach applied. The progression in number of publications excluded at each step is shown by the dotted lines.

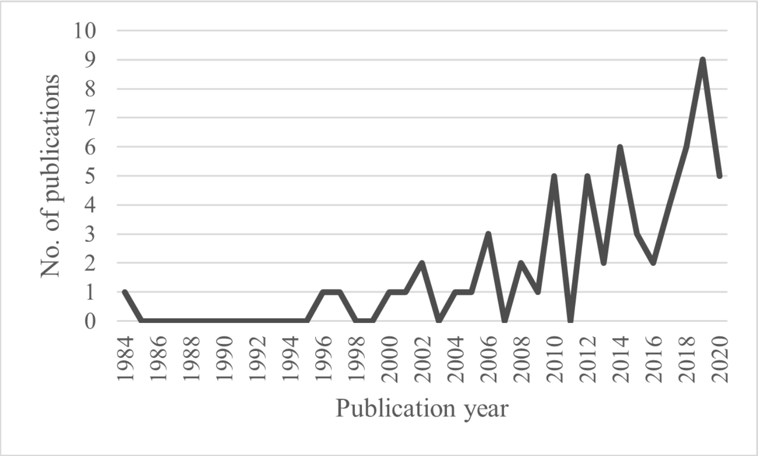

Figure B3. Publication trend of all publications included in the study from 1984 to 2020.

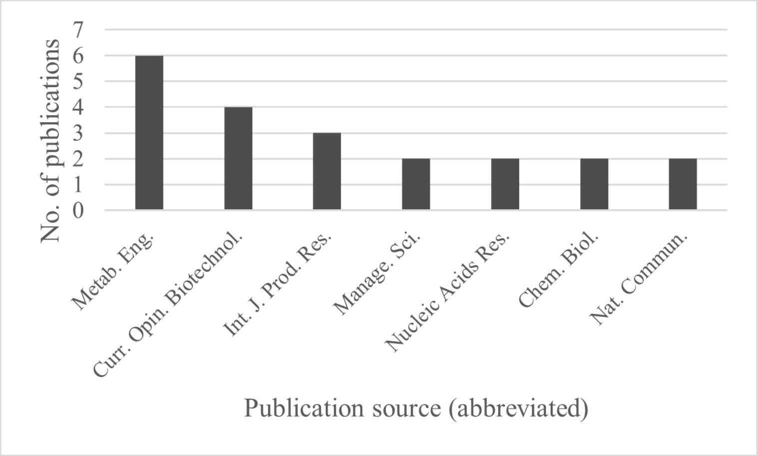

Figure B4. Publication frequency by publication source for all outlets with at least two publications included in this study.

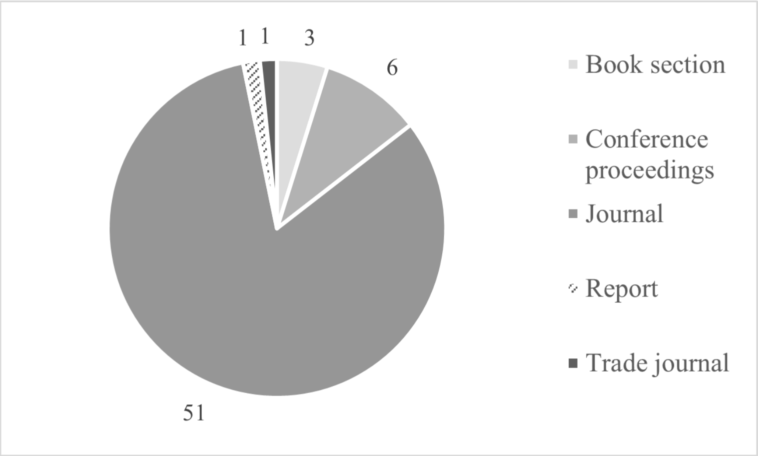

Figure B5. Distribution of publications by publication source type.

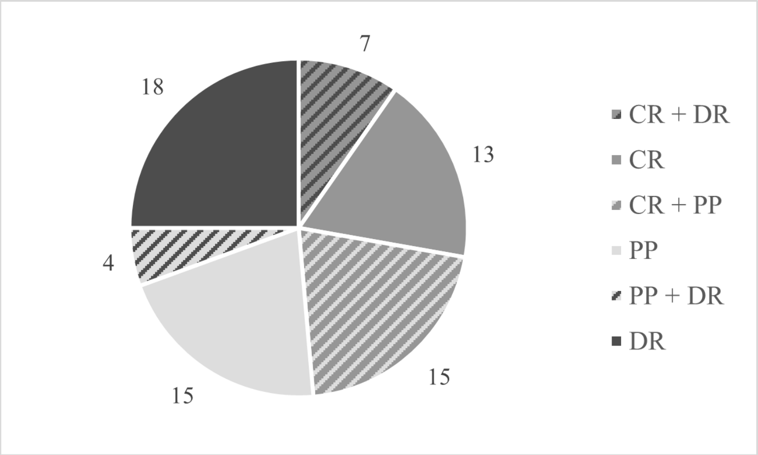

Figure B6. Distribution of drivers identified among the included studies. Drivers are shown by category including compound categories marked by the striped regions (CR = cost reduction, DR = development lead time reduction, PP = productivity of product development).