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ORIGINAL PAPER

An early-phase design process to enable long-term flexibility in assembly systems

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Abstract
Assembly systems require to be designed considering flexibility from a holistic perspective to produce the variety of current and future product generations. Reactive ad hoc changes after realizing both the product and assembly system designs require considerable effort and may even be impossible. A systematic collaborative approach that concurrently considers the early phases of product and assembly system development appears to be essential for working with long-term changes. To this end, a greater understanding of the working procedures and design activities concerning flexibility is required. In this paper, this is investigated based on a theoretical framework and a multiple case study at a world-leading manufacturer of heavy-duty vehicles. As a result, a developed early phase design process to enable long-term flexibility in assembly systems is presented. The theoretical implications provided and the findings are also relevant to those involved in the design process of flexible assembly systems.

Keywords Design process · Early-phases · Flexibility · Assembly system · Electromobility · Reconfigurability

1 Introduction

Every product and assembly system undergoes a design process that is crucial for success (Bellgran and Säfsten 2010) and can be a source of competitive advantage (Wheelwright and Clark 1992). Because modern production is becoming increasingly complex and must adapt to dynamic changes to accommodate product variety (ElMaraghy et al. 2013), the ways the variety is considered during the design of products and the corresponding assembly systems need to be reviewed.

In manufacturing firms, assembly systems play a critical role in creating product variety from a limited array of components and subassemblies (Hu et al. 2011). The importance of flexibility increases according to the level of variety that must be handled (ElMaraghy et al. 2013). *Flexibility* can be defined as a system's ability to change its state without incurring substantial costs in terms of expense, time, effort, or performance (Toni and Tonchia 1998; Upton 1994). This concept has been applied to assembly systems (Koste and Malhotra 1999; Koste et al. 2004) and products (Bischof et al. 2008). To assemble variety of products, machine flexibility is required to perform various operations (Koste and Malhotra 1999). It has also been noted that a flexible assembly system can have a certain level of reconfigurability (Kampker et al. 2019a; Wiendahl and Heger 2004). According to Koren et al. (1999) *reconfigurability* allows changes in the structure, hardware, and software to adjust the capacity and functionality of the system easily and quickly. For instance, it enables the exchange of workpiece carriers (ElMaraghy and Wiendahl 2009) or change in a system's configuration by moving or integrating production equipment and thus provides customized or focused flexibility within a short time frame (ElMaraghy 2006; Koren 2010). Demand for high product variety and short product life cycles compel installed factories and manufacturing technologies to produce current and future product generations (ElMaraghy and Wiendahl 2009). Therefore, assembly systems must be designed to enable changes in flexibility and reconfigurability to minimize product development times and accelerate the introduction of new products and variants (ElMaraghy and Wiendahl 2009) in the long term. Products should also be designed to enable changes and be consistent

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with the existing assembly systems. According to Ross et al. (2008), designing changeable systems with such capabilities increases the value delivered over the lifecycle of a system. However, designing for flexibility is challenging because the optimum method to achieve the flexibility needed to handle and adapt new systems during the design processes is still unclear (Kouvelis et al. 2005).

To manage the increase in complexity, companies need to focus on both their products and the production of the products in a collaborative manner. A deep understanding of work processes, which defines the organization of the design process work, seems to improve product performance and the corresponding process development significantly[1] (Lager 2002). The front-end phases of product development or the *early phases of technology development* can be regarded as the initial phase of the stage-gate innovation process in product development (Cooper 2008) where a product concept is created. From a production development perspective, the *design process of assembly systems* can be regarded as the early or front-end phases of assembly system development, during which the concept of an assembly system is created before its in-depth detailed design for implementation and ramp–up (Bellgran 1998; Bellgran and Säfsten 2010) potentially becoming a process innovation. Evidently, product design and production design processes should be coordinated. Various authors continue to argue that the parallel implementation of product and production development should be explored further (Vielhaber and Stoffels 2014), particularly during the early stages before the formal initiation of product development (Nihtilä 1999; Steimer et al. 2016). However, this is difficult to achieve; even today, the planning of assembly system designs normally starts only after gathering information originating from the late phases of product development (Steimer et al. 2016) and product and production designs are often implemented sequentially even though the wisdom of doing so has been questioned for over 30 years (Guérineau et al. 2022; Takeuchi and Nonaka 1986). The implementation of reactive ad hoc changes after the realizations of both products and production designs requires considerable effort and may even be impossible. Therefore, early phase interventions appear to be essential.

Few studies have examined production development from an early or front-end phase perspective (Frishammar et al. 2013; Kurkkio et al. 2011; Sjödin et al. 2016), and most of these studies focused on process industries such as mining industries, which are different from, for example, vehicle manufacturing industry. Studies have been conducted on process development in manufacturing (Athey and Schmutzler 1995; Cabagnols and Le Bas 2002; Reichstein and Salter 2006); however, the process of developing assembly systems has not been studied as deeply as the product development process (Bellgran and Säfsten 2010). Even though studies pertaining to product development processes focus on issues relevant to assembly, such as product architecture decisions, they do not generally bring up the assembly-system design process. In addition, very little is known about the influence of assembly-system design processes conducted in parallel with the early phases of technology development on flexibility.

Design processes serve different purposes (Wynn and Clarkson 2018) and are influenced by the complexity of the context in which they are applied (Gericke and Blessing 2011; Maffin et al. 1995). Sustainability and Industry 4.0 are the current critical driving factors for changes in manufacturing industries and require more attention in design the processes. Climate change necessitates sustainability in both the transportation sector and society. Partially for this reason, the automotive industry has recently witnessed several advances in electromobility, connectivity, and automation, all of which have disruptive potential with respect to mobility (Sprei 2018). Interest has been growing in finding flexible solutions for electric mobility (Kampker et al. 2019b). Such solutions require radical changes in vehicle powertrains; however, there is uncertainty regarding the transformation of the transport sector, and the internal combustion engine is likely to remain relevant even after 2030 (Springer India-New 2016). Therefore, manufacturers are investing heavily in the development of new electric vehicles and components, such as batteries, and the assembly systems needed to introduce these new radical products while supporting their existing diverse product offers.

In addition, flexibility is expected to improve owing to the emergence of new production paradigms associated with Industry 4.0, such as mass customization and personalization of production (Davies 2015), and the promotion of other technological advances and digitalization of production systems design (Bortolini et al. 2017), for example, by introducing connected factories and new manufacturing technologies. Therefore, manufacturers must address the challenge of integrating new manufacturing technologies and specific customer solutions. Hence, manufacturing industries are moving towards a more flexible production (ElMaraghy 2019), which should be holistic. Accordingly, their design processes should be structured with a long-term view from early phases. Therefore, research on design and development processes is important (Wynn et al. 2019).

1.1 Purpose and scope

Considering both product and assembly system characteristics in parallel during the early phases is important to handle

[1] Production development is also referred as process development (Bellgran and Säfsten 2010). In this article, production refers to assembly.

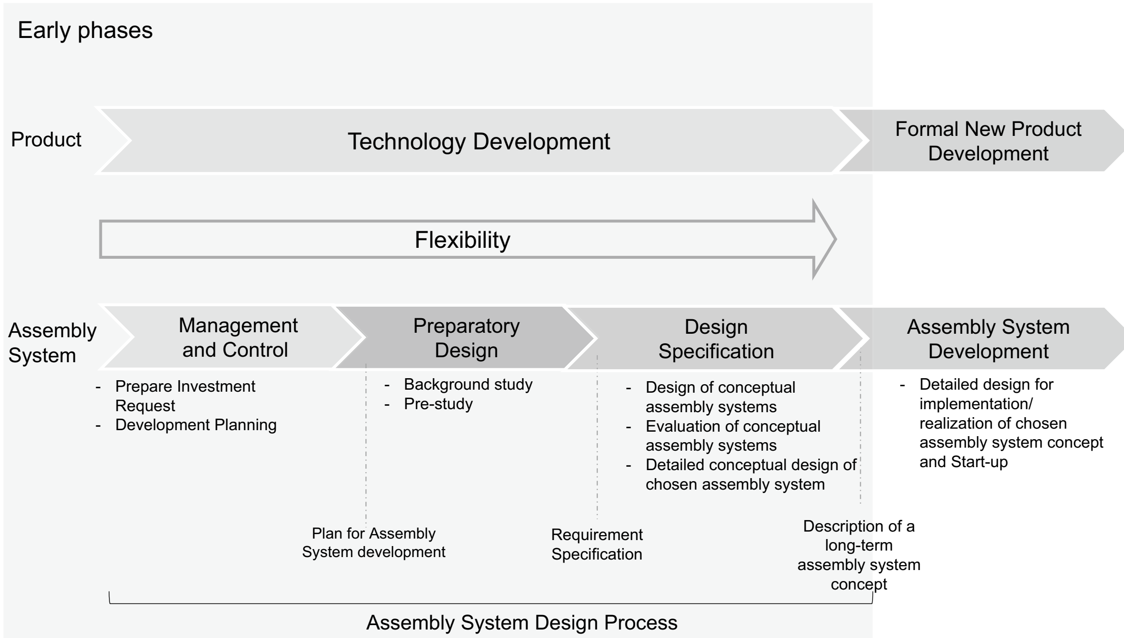

Fig. 1 A conceptual model for the early phases of assembly system and product development according to the theory

the current change drivers in manufacturing; however, a way to work incorporating a holistic long-term view of flexibility during the design remains unclear. This article seeks to contribute to bridge this gap by exploring how to address flexibility during the early phases from the perspective of assembly system design. Recognizing that design processes are characterized by a level of complexity that prevents comprehensive description using a single model (Wynn and Clarkson 2018), this article focuses on the working procedures and activities that can be performed during the design process to enable flexibility. The main findings presented in this article are expected to contribute to engineering design theory by proposing an early phase design process to enable long-term flexibility in assembly systems. This design process also provides managerial support for reducing the complexity of assembly system design in an industrial context characterized by continuous change.

To this end, a case study was conducted to support theoretical development (Eisenhardt 1989; Ketokivi and Choi 2014). Only limited empirical information is reported in the literature; hence, empirical data were collected by examining multiple sources of evidence and active participant observations on two industrial design projects conducted over 6 years at a world-leading heavy-duty manufacturer. The firm is advancing towards electromobility while using combustion engines for some products that address the current manufacturing change drivers mentioned earlier. The studied projects are theoretically relevant (Eisenhardt 1989) because they relate to the design processes of assembly systems that (1) accommodate mixtures of existing products and (2) enable new product flexibility, such as in the case of an autonomous electric heavy-duty vehicle.

This article is divided into six sections, the first of which presents the introduction. Section 2 briefly reviews the literature constituting the theoretical framework of the analysis. Section 3 describes the methods and techniques used in the study. The empirical results and their analysis are presented in Sect. 4. The proposed early-phase design process is presented in Sect. 5. Conclusions, managerial implications, limitations, and future research are presented in Sect. 6.

2 Theoretical framework

This section presents the theoretical background. It is divided into three subsections: (1) theory of early phases, (2) theory of assembly system design processes, and (3) design processes for flexible assembly systems.

To illustrate the context of this paper, a conceptual model for the early phases of the assembly system and product development, according to the theory presented in the following sections, is shown in Fig. 1. The assembly system design process was developed based on Bellgran (1998), and Bellgran and Säfsten (2010).

2.1 Early phases of development

In literature, the early phases of product and production development are often referred to as the front-end phases (Koen et al. 2001; Kurkkio et al. 2011). Generally, these phases include idea generation and activities for achieving a feasible conceptual design. In the manufacturing context, early phases can also be defined as the preparation and structure planning phase (Steimer et al. 2016); for example, the production team prepares and plans the introduction of a new product. Product development has been studied extensively; however, only a few studies have examined the front-end phases of production development (Frishammar et al. 2013; Kurkkio et al. 2011; Sjödin et al. 2016). In addition, these studies focused on process industries, such as mining; hence, very little is known about the early phases of production development in the manufacturing industry. Nevertheless, much can be learned from these studies. Kurkkio et al. (2011) identified several distinct phases in the front-end stage of production development, each involving specific activities. These phases were as follows: (1) an informal start-up, in which the key activities were idea generation, refinement, and informal discussions; (2) formal idea-study, in which the key activities were conducting literature reviews, anticipating end-product changes, preliminary bench testing, creating preliminary production concepts, and defining project objectives; (3) formal pre-study, which involves additional fine-graded bench testing, laboratory testing, pilot plant testing, risk analysis, and refinement of preliminary production concepts; and (4) formal pre-project, in which the key activities were specification and selection of a final production concept, construction/modification of process equipment, full- scale testing, feasibility analysis, and project planning (Kurkkio et al. 2011). The factors that drive the initiation of front-end activity and the causes and mechanisms of such initiations need to be understood clearly. It has been suggested that front-end works in production development are often problem-driven, because they are commonly motivated by the idea of changing or modifying the production processes (Kurkkio et al. 2011). However, production changes and modifications in the manufacturing industry are also product-driven; hence, understanding the relationship between production development and product development is equally important (Pisano 1997).

From a process model perspective, the early phases of technology development can be regarded as the initial phase of the innovative stage-gate approach for product development (Cooper 2008). Technology development consists of applied research and pre-development and commences after basic research but before product/production development (Högman 2011, p. 7). This usually involves the establishment of design specifications and conceptualization (Eder 1998; Steimer et al. 2016). Building on previous works, Högman (2011) defined technology development as the investment of effort into developing skills, knowledge, and artifacts that would facilitate product/production development.

The early phases are exploratory and creative stages in which errors can be found and corrected (Eder 1998). The milestones and corresponding deliverables in these phases include the development and evaluation of product concepts and basic product design work, which generates the first engineering prototypes of the end product (Nihtilä 1999). It has long been argued that investing additional time in these phases can be beneficial because correcting problems in later stages inflates costs, especially correction costs (Eder 1998). Therefore, Reich (2008) stressed the importance of including diverse perspectives in the early design phases, arguing that this can have a significant and positive influence on project success. He further argued that inappropriate knowledge management could necessitate the rework of previously executed activities to regenerate knowledge, which would increase the cost of redesign and obstruct quick and effective responses to requests for rapid changes (Reich 2008, p. 2). Additionally, a holistic approach and an integrated multidisciplinary design are needed to avoid failures due to inconsistencies between different design disciplines (Abdoli and Kara 2019), particularly in production. This is because all components of the assembly system must be considered during the design process (Bennett and Forrester 1993), which requires the involvement of different roles and functions; focusing only on the technical aspects creates problems.

Despite the importance of early phases in working with changes and adaptations in products and production systems, the integration of these processes to consider flexibility has been underexplored. Consequently, little is known about the actual work done in the design of assembly systems in manufacturing firms during the early phases of technology development for flexibility, before the initiation of a new formal product development process.

2.2 Design processes of assembly systems–the how

The process of designing an assembly system is defined in part by the activities performed during the design. Therefore, it encompasses procedures that guide the design work and the creation and selection of an assembly system proposal under the prevailing organizational structure. In addition to procedures and activities, design processes are characterized by the involvement of specific people, use of particular knowledge, an array of tools and methods, and establishment of an economic context (Blessing and Chakrabarti 2009). Design in firms can be carried out without the formulation of defined processes; however, models and supporting concepts have been created to explain and guide their development. Based on prototypical models and concentrating on common patterns of design methods, Gedenryd (1998) defined four fundamental principles for design processes: separation, logical order, planning, and product–process symmetry. The last of these principles states that the structure of the design process should reflect its expected outcome (Gedenryd 1998).

In the context of this article, the way of working along the process to obtain flexibility is still a challenge.

Production development is an uncommon term; in this article, it is referred to as assembly system development, (Vielhaber and Stoffels 2014) and the underlying concept has also been called process development (Bellgran and Säfsten 2010) because it concerns the production process. To date, it has received less attention than product development processes (Bellgran and Säfsten 2010, p. 5); the literature on design and product development models goes back to the early 1960 s (Roozenburg and Eekels 1995). However, despite the growing popularity of the stage-gate model (Cooper 2008), a survey conducted by the Product Development and Management Association found that only 49.1% of the participating companies had a formal, cross-functional process for new product development (Markham and Lee 2013). Moreover, even when product development processes include issues relevant to assembly, such as decisions relating to architecture (modular or integral) (Ulrich and Eppinger 2012), product structure (details, components, and modules) (Johannesson et al. 2013) or other relevant aspects such as design for assembly (DFA), they do not generally bring up the assembly system design process. Indeed, previous analyses have shown that design processes are commonly isolated and do not explicitly address the iteration of other processes or their role in the creation of final products (Gericke and Blessing 2012). Therefore, the design processes must be elucidated from an assembly-system perspective; however, there is limited empirical information.

Some notable studies conducted on production system design processes, methods, and approaches are as follows (Engström et al. 2001; Nof et al. 1997; Rampersad 1994; Suh et al. 1998; Wu 1992). Bellgran (1998) developed a method to support the planning of an assembly system design process, in which the process was divided into different phases and activities. This is probably one of the most detailed works on assembly system design because it addresses management and design aspects, both of which are vital for generating adequate support during a design (Gericke and Blessing 2012). The steps needed to select a system solution according to this method are as follows: (1) design process management, which involves preparing an investment request and a development plan; (2) preparatory design, which involves conducting a background study and pre-studies; and (3) design specification, which involves designing and evaluating conceptual assembly systems and then creating a detailed design of the chosen assembly system (Bellgran and Säfsten 2010). This model differs in some respects from the design process phases observed by Gericke and Blessing (2012) in their study on design process models across disciplines. According to Bellgran (1998) and Bellgran and Säfsten (2010) the implementation of the design and all phases thereafter are considered to be part of the development process rather than the process of assembly system design. Thus, the initiation of the design process is governed by management and control; resource allocation and development planning must be conducted to adapt the design to the requirements of the firm. After the initial planning and allocation of resources, a background study and pre-study are conducted, which involves analyzing, creating a description of the task, gathering additional information, and stating requirements. This is followed by an evaluation phase that occurs between the conceptual phase and the initiation of the detailed design (Bellgran and Säfsten 2010). Additionally, evaluations provide input for a more detailed conceptual design which will be still further detailed for implementation. Assembly system design processes define the preconditions for the development and implementation of an assembly system and should incorporate a way to achieve flexibility. Therefore, understanding the manner by which these design processes relate to flexibility outcomes in terms of ways of working during design, key activities, and critical factors is important.

2.3 The design process of flexible assembly systems

Flexibility is the ability to cope with changes spanning different dimensions, some of which (e.g., mix and product flexibility) relate to product variety. According to Koste and Malhotra (1999), mix flexibility can be defined as the number and variety of products that can be produced without incurring significant transition penalties or substantial changes in performance outcomes. Product flexibility consists of modification flexibility and new product flexibility, which refer to the number and variety of product modifications and new products that can be introduced, respectively, without incurring significant transition penalties or changes in performance. However, other flexibility dimensions include machines, labor, material handling, and volume. The period over which these changes are implemented should also be considered; depending on the pace of change, flexibility may be operational, tactical, or strategic. Strategic and long-term flexibility generally requires greater effort than operational flexibility (Koste and Malhotra 1999). The relationships between different flexibilities in manufacturing contexts have been investigated (Browne et al. 1984) and it has been shown that some flexibility objectives can only be achieved with the support from other types of flexibility. For instance, firms require, among other conditions, the support from machine flexibility and material handling flexibility to achieve mix flexibility (Svensson Harari et al. 2014). This adds complexity because it necessitates a deeper understanding of the relationship between the design and flexibility of assembly systems (Terkaj et al. 2009b) in addition to the relationships between flexibilities. Flexibility has gained widespread recognition as a requisite in designs or systems

(Saleh et al. 2009). However, despite the efforts discussed above, little is known about the design or implementation of such flexibilities at a desirable level during the production-system design processes (Kouvelis et al. 2005). In addition, flexibility is dependent not only on the properties of the assembly systems. Several approaches for developing flexible products exist (Bischof et al. 2008; Crossland et al. 2003) and they should be investigated further to assess their impact on the overall flexibility of the assembly. A long-term and holistic perspective is needed to achieve flexibility, especially if firms want to reuse and adapt existing facilities, equipment, and resources for offering variety while managing both current and future changes effectively. Complexity relies heavily on the way the diverse dimensions of flexibility and their relations are incorporated during the design process. If successful, this can enable a continuous adaptation to change and the integration of other (new) elements, minimizing the risks of incurring negative consequences.

Flexibility can also be achieved via *reconfigurability*, which involves rapid changes in the structure, hardware, and software to adjust capacity and functionality quickly (Koren et al. 1999). Reconfigurability characteristics such as modularity, integrability, diagnosability, convertibility, scalability, and customization have been analyzed, providing insight into issues such as their influence on configuration and reconfiguration and the qualitative relationships between them (Napoleone et al. 2018). Based on a literature review, Anderson et al. (2017) attempted to propose a reconfigurable design process for manufacturing systems and highlighted the remaining challenge in finding ways to express the need for change over a system's lifetime (Andersen et al. 2017). This seems to become more complicated if the assembly systems and product design processes are not sufficiently consistent. Assembly systems must be designed to handle increases in product variety (Hu et al. 2011); therefore, design processes should be reviewed to address these challenges. Some steps in this direction have been taken by researchers studying the context of flexibility in changing customized demands (Bennett and Forrester 1993; Molitor et al. 2017; Rauch et al. 2019; Steimer et al. 2016; Wiktorsson 2014). However, challenges remain, such as understanding not only what to do but also how to perform design activities (Gericke and Blessing 2012), especially those related to enabling flexibility. In addition, differences exist in content between these approaches and the scope of their applicability. Similar to the approaches of Molitor et al. (2017), Rauch et al. (2019) and Steimer et al. (2016) emphasized supporting early phases. Furthermore, in addition to technical aspects, a holistic view of the components of the design process is necessary (Abdoli and Kara 2019; Bennett and Forrester 1993). Studies on the components of the design processes for flexible assembly systems and their integration have been presented elsewhere (Svensson Harari et al. 2018). The results of such studies are important because flexibility is a multidimensional concept with many different interpretations and foci (Allvin and Aronsson 2013) which have been defined from a wide range of perspectives (D'Souza and Williams 2000). Firms are aware of the challenges associated with, for example, achieving flexibility in the context of electromobility (Bichler et al. 2018; Köhl et al. 2018) and they recognize that, despite the existing theoretical and industrial contributions to the field, current mechanisms for identifying approaches for planning flexibility may not be applicable (Kampker et al. 2019a).

While the aforementioned contributions reflect a tendency to consider product flexibility, the ways in which flexibility is addressed differ among the reported approaches. When handling and adapting for product variety, the roles of the products and the corresponding processes during the design of flexible assembly systems and their interrelations must be considered. The introduction of innovative products, such as electrified vehicles, can entail both radical innovations during the early stages of diffusion and adoption and incremental innovations during the later stages of the product life cycle (García and Calantone 2002). Similarly, the adoption of a life-cycle perspective in the design of assembly systems can be motivated by two factors: the need for a new system or the need to replace or modify an existing system (Karlsson et al. 2009). Vielhaber and Stoffels (2014, p. 252) claimed that the lifecycles of a product and the equipment used in its production intersect during the product's production phase, which corresponds to the use-phase of production equipment. Therefore, products and production equipment should be developed simultaneously rather than more or less independently, as they are typically developed today (Vielhaber and Stoffels 2014). Moreover, the findings of Reichstein and Salter (2006) suggest the existence of complementarities between product and process innovations, through which new products can entail the creation of new processes and vice versa. Hence, product and process innovations may be related in practice. Cabagnols and Le Bas (2002) found that stronger flexibility strategies (quantified in terms of a variable measuring the importance of flexibility in relation to technological change) increase the probability of concurrent product and process innovation relative to that of product innovation alone, without reducing the probability of process innovation. Therefore, it is important to understand and characterize the magnitude of the changes that can be achieved in both products and production during the early stages. Such an understanding could have important implications for assembly system design processes. For instance, the impact of introducing new products could differ from that of introducing new variants/options or expanding the variety of existing products handled by one system and could thus necessitate different levels of flexibility. This seems particularly relevant since a principal barrier to integrating flexibility into the decision-making process is the difficulty of measuring and comparing it under undefinable future production scenarios (Abele et al. 2006).

Emerging approaches such as the co-development of products and production systems emphasize the interconnections between product changes and manufacturing systems (Michaelis 2013) and working with product platforms and manufacturing platforms simultaneously (Abbas and ElMaraghy 2018) to achieve flexibility. Activities such as defining the market and creating product and production architectures have also been claimed to contribute to flexibility by improving synchronization between product and production development (Mortensen et al. 2011). *Product architecture*, which is decided during the early phases of the innovation process and R&D, often plays a lead role and "is the scheme by which the function of the product is allocated to physical components." It includes specifications for the arrangement and mapping of functional elements to physical components and the interfaces between interacting physical components (Ulrich 1995 p, 420). A *modular architecture* "includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components," in contrast to a complex (non-one-to-one) integral architecture (Ulrich 1995 p, 422). Products with a modular architecture can be more easily redesigned (for upgrading or diversification of a product family) (Engel et al. 2017). Deciding the appropriate amount on modularity has been found crucial. The application of design for adaptability concepts based on the architecture option (AO) theory (Engel and Browning 2008) in different industries, including automotive and machine tools, has been shown to contribute to benefits such as the reduction of lifetime cost and upgrade cycle time and the increase of lifespan of systems (Engel and Reich 2015). In addition, managers' influence on architectural evolution is retained as products become more mature, allowing the co-evolution of modularity and innovations (Engel et al. 2017).

Mortensen et al. (2011) indicate that modelling the *market architecture* consists of deciding the coverage of the product family. The *product architecture* describes the building principles for a product family, and the *production/supply architecture* describes the building principles for production and procedures to support launches of future derivative products. It includes generic assembly system flows, indicating the necessary assembly equipment and types of standard designs. This is connected to the flexibility of the assembly system by displaying the differences and commonalities of each variant. It also includes assembly line equipment, machinery, tools, mapped towards future launches (Mortensen et al. 2011). The flexible sequence in an assembly line can have a number of constraints, such as ergonomics, component availability, and tool availability (Lafou et al. 2016b). Architecture analysis is usually not part of the design processes of flexible assembly systems; therefore, ways of integrating these activities into flexible design processes are desired. The decoupling of technical systems into distinct increments to derive implications for product architecture design and facilitate highly iterative product development processes has also been proposed (Schloesser et al. 2017). For instance, in the electric automotive sector, car body design and the corresponding production shop have been identified as crucial areas for efforts to increase flexibility (Kampker et al. 2019a).

Overall, there is no consensus regarding the structure of the design processes for flexible assembly systems, the activities that should be included, or methods that should be incorporated to achieve a design with sufficient flexibility. However, there is an emerging tendency to consider the design in the early phases of both product and assembly system development in the current context of mass customization. Furthermore, in the literature, systems are sometimes described as being flexible or reconfigurable. However, reconfigurability has been considered capable of providing customized flexibility (Azab et al. 2013; ElMaraghy 2006). In other words, flexibility can confer a common quality of adaptation within corridors of change, whereas reconfigurability allows the change of dimensions of these corridors by altering the capacity and functionality of the system (Azab et al. 2013). For example, machine builders usually incorporate a certain level of flexibility and reconfigurability into their product designs to accommodate diverse uses during the product's lifetime (Terkaj et al. 2009a). Notably, flexibility levels depend on parameters such as the number of products or its variants representing production volumes and levels of automation (Heilala and Voho 2001; Lotter and Wiendahl 2009; Rampersad 1994).

The following section summarizes the research methods and techniques used to investigate the aforementioned problems.

3 Research methods and techniques

This section explains how the research was conducted. It first presents the overarching research design. Next, it outlines the design of the case study and the methods used for data collection and finally describes the steps taken to ensure the validity and reliability of the collected data and their analysis.

3.1 Research design

Based on the purpose of the study and literature on case studies (Eisenhardt 1989; Ketokivi and Choi 2014; Yin 2014), a multiple case study with an exploratory character was performed. Several factors motivated this methodological choice. First, this research aims to contribute to the development of the emerging theory concerning the design process of flexible assembly systems and, more specifically, in the early phases of technology development by exploring the phenomena in the context of a manufacturing firm. Theories on the early phases of product development, flexible assembly systems, and assembly systems design are already well established. Second, it allows the investigation of the phenomena under real and specific industrial contexts (Yin 2014). This was facilitated by a collaboration framework established between the university at which one of the authors studied and the participating firm, based on their common interests in flexibility and development processes. As a result, the author was granted access to conduct research in the firm during her PhD studies and was able to observe relevant cases. This was important to understand the direction of the design processes in an industrial context because processes can be considered "both constrained by context and shape contexts, either in the direction of preserving or altering them" (Pettigrew 1990, p. 270). The researcher assumed the role of a participant observer for data collection and engaged in the activities of the cases being studied (Yin 2014). A participative and interactive approach (Ellström 2007), in which the researcher retained an independent role, was adopted. Third, it facilitated the reliance on multiple sources of evidence (see Appendix 1), allowing the use of triangulation (i.e., seeking at least three ways to verify or corroborate events, descriptions, and facts) to determine the consistency of a finding (Yin 2011, 2014). Fourth, case studies are considered valid by practitioners and can contribute to the development of theory (Voss 2009). This was relevant to the collaborative framework adopted in the conducted research. Multiple case studies can support the development of a more robust theory because the resulting propositions are deeply grounded in varied empirical evidence, which enables a broader exploration of the phenomena under investigation and more extensive theoretical elaboration (Eisenhardt and Graebner 2007, p. 27). In turn, this generates a broader and more general theoretical understanding (Eisenhardt 1989; Yin 2014). Case studies also contribute to the "collective process of knowledge accumulation in a given field" (Flyvbjerg 2006, p. 227).

3.2 Case study design

The cases were selected based on theoretical considerations and their relevance to the research topic and objective. The uniqueness of the cases and the likelihood of obtaining sufficient access to data were also considered (Yin 2014). Two case studies were conducted on a heavy-duty manufacturer that has factories around the world, is active in over 150 markets, and employs over 10,000 people. The product range includes at least 15 main products, each of which has several models, variants, and options adding up to more than 100 products. The manufacturer produces custom-made machines also. Two cases (Case I and Case II) provide different contexts relevant to this work (see Fig. 2); they are described below.

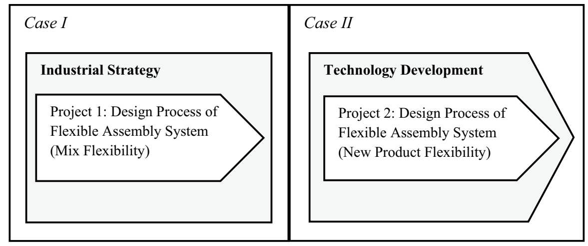

Fig. 2 Context of the cases (Industrial Strategy and Technology Development) and unit of analysis (Project 1 and 2)

Case I is a project within the firm for improving the development of products and production systems in terms of flexibility. It focused on assembly, with the objective of producing several different products in one assembly line (mix flexibility).

Case II is a sub-project originating from a major advanced engineering (AE) research projects of the firm on electromobility, automation, and connectivity. The sub-project is focused on generating alternatives for the assembly of an autonomous electric heavy-duty vehicle to enable potential industrialization, starting from a fleet of seven prototypes (new product flexibility). The main project was a joint effort by the firm, key customers, universities, and the public sector.

The first author conducted research within the projects with the objective of investigating the design process of flexible assembly systems to create an assembly system with the desired capabilities (the flexibility to mix products and introduce new products).

3.3 Data collection

Multiple data collection techniques were applied (Meredith 1998), including participant observation, templates, questionnaires, direct observations, semi-structured interviews, study visits, document studies, informal consultations, and notes. An overview of the case studies and the corresponding data collection techniques is presented in Appendix 1. Triangulation strategies were used to converge evidence from different sources.

Participant observation (Yin 2014) was made possible by the first author's involvement in the studied cases. This enabled data collection using several methods. Participant observation is considered advantageous because it allows the acquisition of direct observations that can help explain the how's and why's of a phenomenon (Meredith 1998) and it provides different contexts and opportunities for improving the depth of observation (Voss et al. 2002). It also enables the observation of the sequential progress of processes and their evolution over time (Pettigrew 1990), and it facilitates in-depth analysis of design processes with the subject of the study delimitated clearly. This, in turn allowed the researcher to focus on the scope of the observations based on the objectives of the research (Creswell 2014). A key objective in this work was to understand how designers worked within the framework of the research objectives relating to flexibility and to characterize the inherent challenges of design processes such as separation—a characteristic that presents some challenges but also supports logical order, planning, and product-process symmetry according to Gedenryd (1998).

3.4 Data analysis

The data gathered were analyzed using the procedures proposed by Yin (2011) and Miles and Huberman (1994). The analysis process began during the conceptualization of the project, and observations made during data collection were subjected to a selective process (Miles and Huberman 1994) based on the theoretical framework. The participant researcher's involvement in gathering the data ensured better and specific knowledge of the material during the analytical process.

Initially, the observations from each case were compiled separately and subjected to a data reduction process involving selection, transformation, simplification, and integration (Miles and Huberman 1994). The chronological order of the data gathered was preserved during this process because it was regarded as an important source of information on the evolution of the design processes.

The collected data were disassembled and reassembled by coding and creating categories and themes relating to (1) the context, scope, and purpose of the projects; 2) the organization of the projects; (3) challenges and enablers; and (4) phases and activities related to the design processes for flexible assembly systems. This was a mixed process in which codes were inferred or arose from the material, but were also imposed by theory and the research objective. The theoretical framework was used to interpret the results by finding patterns, sequences/causal chains of events, relations, and logical orders that could serve as an initial basis for conclusions. The analytical process incorporates both identification and confirmation activities. The cross-case analysis involved comparing the cases to identify their similarities and differences and comparing the observations to the theoretical principles discussed in the preceding sections.

3.5 Validity and reliability

Construct validity was secured by gathering evidence from multiple sources (Yin 2014) to enable triangulation. Methodological triangulation (Denzin and Lincoln 2017) and data triangulation (Yin 2014) were used. Methodological triangulation was achieved by capturing data from different sources, including documents, observations, and semi-structured interviews (Appendix 1). Data triangulation involved verifying that the findings obtained from different sources corroborate one another. For example, the responses of study participants to certain questions were compared with the available documentation to establish the convergence of evidence (Yin 2014). The member checking and prolonged engagement strategies proposed by Creswell (2014) were also applied to secure accuracy through contact with participants and by developing an in-depth understanding of the phenomenon under investigation (Creswell 2014). Although the study was founded in theory and the observations were continuously analyzed and discussed in relation to theory while the study was ongoing; the external validity of the conclusions could be limited because the empirical findings related to a single company. However, this is counterbalanced by the varied empirical evidence provided by the cases. To maximize the reliability, the procedures are described transparently. Finally, a risk of potential bias created while acting as a participant observer was counteracted by the unique opportunity provided by this role to collect rich data (Yin 2014) and the suitability of participant observation for studying design processes (Blessing and Chakrabarti 2009). In addition, the researcher mitigated this risk by applying multiple strategies to ensure the quality of the research: the researcher (1) elucidated the role as a PhD student to all the involved parties from the outset of the study, (2) used triangulation, (3) independently designed the studies, (4) clearly defined the theoretical background of the research, (5) applied appropriate research techniques and data collection instruments, and (6) analyzed and inferred the conclusions independently. The researcher's status as a participant observer and involvement with the projects also offered valuable opportunities to obtain feedback on the study's findings to enrich subsequent discussions.

4 Empirical findings

This section presents the cross-case analysis and highlights the differences between cases. The presentation of the findings reflects the analytical logic outlined in the Research Methods and Techniques section.

4.1 The context, scope and purpose

Case I was strongly connected to the company's firm-level strategy. The key elements of this strategy included the customization of all products in production hubs close to the customer, increasing manufacturing flexibility, shared technology, common architectures in products and assembly systems, effective development, and improved quality. This strategy guided the concept development in the project to mixed-model assembly lines with a common assembly sequence. The objectives were to define, reduce, and optimize manufacturing concepts to create a production line capable of producing any of the company's current products or product variants at any time. An additional goal was to identify the operational requirements that products and processes must satisfy to be compatible with the proposed solution and the activities that would be necessary for the solution's development. The project was firm-level coordinated and the related projects were on issues such as the analysis of product architecture.

Case II also aligned with the company strategy mentioned above; however, it originated from a research exercise related to the company's manufacturing research and AE. The knowledge generated in Case I was expected to contribute to the project's advancement. The focus was on new electromobility products, specifically, an autonomous electric heavy-duty vehicle. This technology was developed over many years and; the concept was first developed in 2011. Subsequently, pre-studies and cost analyses were performed. The first prototype was built with support from a student project in 2014/2015. A second-generation prototype was then developed, and the objective of the main parent project of Case II was to build a fleet of seven prototypes of this machine that could be piloted in a customer's workplace. The vehicle's development had already deviated significantly from the typical development processes of the firm when the case study began. Usually, AE personnel build a prototype without the involvement of production staff. Instead, the latter works on a new product development (NPD) project and observes different product statuses for achieving optimal production. In contrast, in Case II, the production personnel contributed to the building of the AE prototypes, especially the most recent fleet, and created other preconditions for the following development phases.

Common to both projects was the objective of generating assembly concepts/alternatives that provide flexibility (flexibility to mix different existing products in the same assembly system and flexibility to introduce new products in the assembly system). Thus, both projects sought ways to advance towards designing flexibility.

4.2 The design process for flexible assembly systems at the projects

None of the projects had an established design process for flexible assembly systems. Therefore, activities were identified and developed as the projects evolved, and the architecture processes continued to develop after the projects finished. This was partly because both projects focused on subjects new to the firm; hence, the firm needed to improve knowledge, support development, and clarify ways to achieve flexibility in assembly. The production research personnel were deeply involved in both projects. A common practice at the firm was to focus on product prototype building during the early phase of projects; however, a greater focus on preparing production was desired. This was referred to as operations front loading.

Five critical stages were identified in the studied projects: (1) the vision, initiation, and organization of the projects; (2) review of the current situation; (3) specification of requirements; (4) conceptual design; and (5) evaluations. The activities performed during these stages are described below.

1. *The vision, initiation, and organization of the projects*: Case I was a strategy- and production-driven project (initiated by a strategy but managed by operations/production) with the aim of developing mixed-product assembly lines (mix-flexibility), whereas Case II was a product-driven project (initiated by a new product development) with the aim of facilitating new product flexibility and supporting the handling of different products in the same line. Defining objectives regarding flexibility was important in both cases, and a clear vision of the project's purpose was needed to define the techniques for achieving it. This was particularly challenging in Case I, in which more strategy-related inputs were required. The project studied in Case II was motivated by a more general vision of finding the best approach for manufacturing a product in a way that would facilitate industrialization. Because of the early stage at which these activities were conducted, the availability of relevant facts was considered important for shaping the vision and defining the "wanted position" for producing electric vehicles.

Unlike the Case II project, the Case I project had been formally allocated resources and time since its inception but had limited interaction and collaboration with product development. This is an important difference. Project participants in Case I tried to interact with product-side personnel to convey information about important assembly issues. Despite this, the final assembly concept was heavily influenced by product design, and its design implementation was heavily constrained by the limited scope for making changes in the product. Conversely, the work done in Case II was initiated in part because of a request from the product-side personnel who were significantly involved with the project from its beginning. These different levels of product inclusion influenced the organization of the projects in the two cases.

Case II was not initially planned when the AE project was initiated. The resources and time allocated for production were mainly intended for prototype building; therefore, the resources from production were limited in the project. As a result, production personnel working on the product during the AE project commonly made remarks such as. "..*resources should also be allocated for production.*"[2] However, the adoption of a participatory and flexible approach involving the creation of awareness and knowledge sharing allowed the project to attract interest and the organization to assume different active roles and functions from the beginning. One recommendation that emerged from the team members' experiences during the project was that the participation of production personnel should be formalized by assigning them resources and time for development work, rather than only for machine prototyping. Specifying roles, responsibilities, and interactions were also considered as important. On several occasions, both product and production personnel stressed that their "*way of working… is all about collaboration.*"[3]

Both projects were assigned to a relatively stable team, with additional personnel joining and leaving, depending on the activities performed. Identifying key roles was important for securing support and ensuring that the team possessed the competences needed to perform the design activities. The important roles identified in Case I were as follows: a project manager (under a steering committee) skilled in both project management and research, someone responsible for production architecture, production engineers experienced with the assembly process under consideration and design tools, managers from the factory in question, a logistics developer who also manages logistical solutions with suppliers, operators (from logistics and assembly), production researchers, someone responsible for simulations, a consultant with experience in production and modular material handling solutions, a reference group including individuals working in other factories, and with the company's production system. These roles were also considered important in Case II, with the exception that no resources were assigned to a consultant. Other roles important for Case II were a project manager skilled in both project management and design, product experts, architecture experts, someone responsible for production preparation, someone responsible for purchasing, someone responsible for prototype building, a 3D CAD expert who could export and work with product designs and generate outputs (e.g., instructions, assembly sequence simulations, or visualizations of the main assembly and subassemblies) in response to production needs, the manager of the development/test area, an individual responsible for safety and quality, and supporting functions, including maintenance, fabrication, product systems, and automation experts. The product side also had researchers and collaborations with other firms of the corporation, suppliers, and customers to provide information about the market and forecast of the products. Additionally, the researchers, consultant and project manager contributed their knowledge about flexibility and reconfigurability in Case I and the researcher contributed in Case II. Finally, as mentioned previously, the participants in Case II argued that securing resources and funding for production was crucial for the success of future design projects.

Interaction and communication between team members was important. Both the cases involved remote collaboration. Common meetings involving members, stakeholders, and users were considered important, and face-to-face meetings were highly beneficial in both projects because they effectively facilitated the progression of the design. In both cases, having a place to store information and make it available to all team members was also important. Particularly in Case II, having a common platform to exchange information and for the production personnel to document and follow up on product criticism was crucial because it allowed product designers to incorporate this information during their own development work. Kick-off meetings involving all project members and close stakeholders were also crucial for sharing information, anchoring the project, enabling discussions, and establishing a common understanding. Notably, in both cases, events were arranged for personnel from various departments of the organization to exchange information about the ongoing work. In Case II, approximately fifty people attended such events, including senior managers, working in technology and operations, and customers.

2. *Review of the current situation* –Products, assembly systems, and material handling were reviewed in both cases, and participants considered these reviews to be key activities in the projects. This includes gathering the requirements and expectations. The review process and its contributions to flexibility are briefly discussed below.

- *Product review:* product review encompasses reviewing dimensions, product modules, components integrating those modules, common assembly sequences, and assembly interfaces (including the manner operators pick, place, and attach the material). The manner in which operators move the material was also highlighted in Case II; the assembly interfaces in this case

[2] Said by a production engineer during the project's first workshop.

[3] Product specialist, workshop operations and technology collaboration.

consisted of picking, moving, placing, and attaching. These processes were evaluated with respect to design criteria such as pick points, directional positioning, ease of access, and performance (ergonomics, safety, time, etc.). The product review and its results directly reflected the product architecture and included the analysis of new product modules in Case II. Interface diagrams played an important role in this architecture-related work because they facilitated the communication between team members in different roles, including operators. Product interface diagrams can also be connected to assembly sequence diagrams. In Case I, this was done by conducting an analysis in the line and based on the experience of operators and production engineers. In Case II, this was achieved using 3D CAD models, prototypes, and feedback from the operators. Complete 3D CAD models were required to generate BOM/BOP and assembly instructions. In addition, the assembly time of the products was known in Case I, whereas it was not completely known in Case II. The latter required efforts to calculate resource requirements and work content and to develop concepts for different volume scenarios. Therefore, assembly time data were obtained by filming during the physical build of the assembly system concept and by obtaining feedback from the operators.

- *Assembly system review*: to analyze the assembly process, templates were created during Case I to understand the current situation in the firm's assembly lines worldwide. These templates provided information about the layout of the existing assembly lines in each station to clarify the modules assembled at the stations, the tools and equipment (both generic and special) used, work content and its changes over time, and the number of operators, groups, and shifts, and so on. In Case II, assembly processes were analyzed by considering the assembly sequence of the modules, which encompassed the equipment used, common processes, new process steps, new equipment requirements, new competences needed, etc. Benchmark activities were conducted to gain an understanding from other industrial settings.
- *Material Handling review*: in both cases, the material handling review examined the number of parts, their commonality, and the presentation of the material. In Case I, templates were used to gather information about the different assembly lines, and the review process included the development of guidelines on material handling. In Case II, the new parts and components were analyzed, and the current presentation methods were examined. The purchasing staff agreed to deliver parts with suppliers; however, feedback from logistics and assembly was also important in this process.

3. *Requirements*: in Case I, the requirements review examined the design criteria, principles of the firm's production system, principles of logistics, key performance indicators (KPIs), and feedback from different stakeholders. These factors were examined in Case II also; however, the review process additionally encompassed identifying new competences, considering new modules and methods of handling the modules, new assembly processes and methods, new manufacturing technology, the need for training in electrical safety, safety roles, and standards for electrical installation and handling of batteries.
4. *Conceptual design*: assembly, and logistics were considered during the design process in both cases. Logistics personnel were required to develop feasible plans that were aligned and coordinated with the assembly concept. The concept design commenced after evaluating the current situation clearly. During this process, the characteristics of the products, such as their dimensions (size) and weight, were closely considered to determine the products that could be assembled in the same line. To this end, products were also classified into different groups depending on whether they had a single base, horizontal hinge, or vertical hinge. In Case II, a debate issued on whether the product under consideration would necessitate the initiation of a completely new assembly system and electric vehicle product variants. In both cases, the commonality or adaptation of the assembly sequence, number of stations/zones, layout and available space, sub-assemblies, material presentation, product moving systems, and work content were necessary to review. In Case II, the assembly time was not completely known and was therefore determined during the physical build. The resulting estimate deviated by only $\pm 30\%$ approximately and was adequate for use in subsequent steps. Tools and equipment were also analyzed (as well as the need for new processes and components in Case II), along with assembly interfaces, product feedback, project team organization, competences, and roles.
5. *Evaluations*: both physical and virtual builds were performed in both cases. In Case I, simulations were used to evaluate factors such as the utilization and efficiency of the assembly concepts. Complexity evaluations were also performed from the operator's perspective. The virtual build in Case II was implemented and examined during the course of a joint evaluation exercise involving personnel (19 in total) representing several different roles and areas of responsibility from both the production (including development operators) and product development sides. This group subsequently determined the scope of the evaluation by using different analysis. The assembly sequence was animated, and a compendium with 3D assembly information was used to facilitate the discussion of product changes/adaptation and production deviations, including potential changes relat-

ing to tools, equipment, and ergonomics. The suggested product changes were documented by product designers to record them on a shared information platform and followed up along with other product changes suggested by prototype operators. Production personnel documented the production deviations to use them during the prototype building and serial production. Thus, a basis was established from which production and investment costs could be estimated. Finally, manufacturing readiness levels were assessed and inputs from technology readiness were gathered to achieve similar maturity levels.

4.3 Challenges and enablers

In both projects, achieving mix flexibility and new product flexibility required an analysis of both products and the assembly systems. Both projects were characterized by ongoing discussions on the ways product design changes, based on common design solutions between products, could reduce the need for flexibility in assembly or ways of improving flexibility in assembly to handle different products in the same line.

The requirements of the Case I project included both flexibility and reconfigurability. The new line concept was required for handling different product volumes (volume flexibility) and introducing new variants and products (product flexibility). To minimize time and costs, the concept also allows the system to be configurable for new variants, products, and volumes without necessitating the development of a new line (reconfigurability). It was also necessary to exhibit operational flexibility by using a common assembly sequence with shared technologies and tools for different models and products.

To achieve product flexibility, the firm focuses on three related concepts: modularity, product architecture, and commonality. Modularity was adopted mainly to increase simplicity, as demonstrated by the rhetorical question *"…is there a way to combine a wide product range with a simple setup?"*[4] Modularity is achieved by breaking down products into modules or building blocks that can be combined in different ways to create multiple products from a limited number of modules. Modularity could simplify and facilitate assembly, as explained by the following remark, *"[Low modularity] …is a challenge today because it creates differences between models, for example, between W and A. W has a movable front and back wall, unlike A. Therefore, the ergonomics of working on A are inferior even when it is possible to use up/down tables [in production]; construction [product design] allows us to create a good working environment for employees."*[5]

The systematic organization of modularity, for instance, by clearly displaying the modules' interfaces, was referred to as the product architecture. In principle, the adoption of a coherent product architecture should facilitate the recognition of commonality between modules and products and the merging of assembly lines. Commonality was also considered beneficial for logistics: "…*We have low commonality in X-parts, only for X, the first station gets X meters of material."*[6] During the development of the concept, the logistics division would need to deliver parts sequentially (with the support of system solutions), owing to a lack of allocated space.

A common assembly sequence was also considered important for the creation of a common assembly setup in which modules would progress through the same flow/stations using common tools and logistics to deliver the same part to the same station for all models/products. The assembly sequences were compared across multiple products to identify technically and economically viable solutions. Because the concept was important to the company, the proposals were validated using real checks and tests to establish a proof-of-concept. The proof-of-concept testing showed that *"… the sequence works for different products but some design changes are needed – we have to make the machines more similar from an assembly perspective."*[7] The commonality of parts reduced the number of parts that needed to be managed, costs (product), material exposure on the line, and the space needed for warehousing.

Handling product changes was a major challenge in Case I. Interestingly, however, the project participants recognized that the product design affected the production. A participant remarked, *"…If [the product] is not well designed, it is also expensive to produce. There is usually a focus on rationalization in production instead of thinking about rationalization by creating smart constructions/designs."*[8]

Some team members were assigned to focus specifically on the requirements for NPD and coordinate with staff working with modularity for other projects; two of these participants noted, *"… We need to communicate what is important to us and how we understand interfaces from an assembly perspective."*[9] By collaborating with other projects, a method of working with assembly interfaces was defined to identify the commonalities in product modules based on

[4] Product architecture expert, modularity film from main project information event.

[5] Interview Assembly project coordinator/investments/Layout.

[6] Global logistics developer, project meeting notes and project film.

[7] Project Manager Operations, project proof-of-concept information film.

[8] Interview Assembly project coordinator/ investments/Layout.

[9] Consultant and project manager, notes from a project meeting.

the manner the modules were picked during assembly, positioned for assembly, and finally attached to the products.

Several factors that enabled flexibility in the assembly were identified during the project; they spanned a wide range of assembly system components. Examples include a flat assembly base for easy and fast configuration, generic configuration for all products (layout/infrastructure), standardized and reconfigurable equipment (technical system), moving assemblers and rotation (human system), sequenced logistics/moving material (material handling), digital and customized instructions, and Bill of Materials (BOM) to reduce complexity (information systems).

A common sentiment among project participants was that changes in products should be considered. For example, a participant said that *[Low commonality] "…should be considered during product development (construction/technology); it is more difficult to address later on"*[10] Thus, realizing changes in the company's current products was one of the biggest challenges encountered during the project. The impact of this was reflected in the design of the concepts, because the first step in the concept development stage was to analyze the products and group them according to their characteristics. Implementing the changes required was recognized to take time: *"…We have a long way to go to get full leverage over the project's implementation in all products and at all sites."*[11]

The objectives of Case II were more firmly defined: investigate ways of assembling an autonomous electric heavy-duty vehicle and draw insight from existing/common assembly setups supported by knowledge developed in Case I but with an additional emphasis on new product flexibility. In Case II, modularity, product architecture, and commonality were not integrated into the early phases of the technology development process. In particular, no established procedure existed for finding modules to reuse or use in the development of commonalities. In addition, no established procedure was available to design the architecture from the early phase.

The importance of product changes was also highlighted by the Case II participants, along with the need to understand the requirements of both products and production. For example, after being asked *"…Can you allow X to open from 45–60 degrees to 90 degrees? That would give more space for assembly,"* the product designer answered, *"…To do that I would have to increase the amount of material used in part X, which would be costly*."[12]Addressing changes in a timely manner was considered critical; a commonly expressed sentiment was that "…*With each passing day, there are fewer changes we can make, and any remaining issues will have to be taken care of by NPD."*[13] Early work was considered advantageous because it allowed time to discuss product changes and critiques and to implement adaptations in product and production design.

During Case II, participants were able to work towards defining modules/building blocks, product architecture (by discussing possible future variants and modules that might be affected), common assembly sequences, and the preliminary identification of the commonality of parts. Complete product CAD models were not available from the beginning, which represented a challenge for prototyping. However, because the project was conducted during the early stage, CAD models evolved over time based on product feedback and development work. The files the product designers worked on were available to the production staff and served as the basis for their development. Thus, having complete product CAD models was recognized to be crucial because it enabled work with the bill of processes and detailed information on materials/parts, as well as to visualize components, work with assembly sequences, perform virtual builds, create animations, and generate instructions. Additionally, product designers, production engineers, and development personnel, including operators, reported product design changes and production deviations in a common virtual build based on the affected prototype and serial production. These changes and deviations could then be analyzed in terms of cost and the necessary investment in production. Subsequently, a physical build of the assembly concept enabled the production of several prototypes, which provided data on factors, such as assembly times, and refines the assembly instructions further. The physical implementation of the concept also allowed it to be evaluated in various ways. Together, these outcomes facilitated a more detailed design. Feedback from the product side indicated that this way of working in the early stage enabled. '… *better quality in prototypes and greater prototyping speed.'*[14]

The operators were very active in addressing product critiques and in designing/developing new technology to make it producible. As a production engineer and product specialist pointed out *"…[operators] are also designers."*[15] Their active involvement and feedback were crucial for the project's success. The production staff was trained in new electrical safety roles during the construction of the prototype. In addition, standards related to electromobility were disseminated throughout the organization, which created an

[10] Interview Assembly project coordinator/investments/Layout.

[11] Overall project operations leader, proof-of-concept information film.

[12] Notes from conversation during virtual build.

[13] Product specialist, notes from informal conversation.

[14] Product expert – workshop operations, technology collaboration.

[15] Production engineer and product specialist, notes workshop operations, technology collaboration.

awareness on the new functional characteristics of the product, corresponding assembly processes, new manufacturing technology tested, and the handling and storage of components such as batteries.

The site and means for producing the electric vehicle were not defined at the outset of the project; hence, scenarios were considered to analyze different alternatives. In addition, the purchasing team was in continuous contact with the material suppliers. The delivery of components was discussed in meetings organized by product designers, which were participated by purchasing and production personnel. A major question was whether to sign long-term agreements, secure contracts to cover the building of the prototypes, or find an intermediate arrangement. The delivery time was also important. Reaching agreements with suppliers and arranging the delivery of parts was important because the firm wanted to ensure a potential delivery of the designed components in the future. However, specifying the quantities needed was challenging because of the ongoing design work, even though the contract would require the suppliers to deliver the parts to the firm. In addition, the prototype fleet was unusually large (consisting of seven machines), and the reception area of the firm' was not structured to accommodate a prototype project of such a scale. Therefore, new arrangements were required.

A recurring challenge central to both projects was commonality. The integration and merging of new and existing systems by identifying adaptations were crucial in Case II; however, the main difference was that in Case II, these concerns were handled at a point when it was still possible to make changes to the products based on the production situation. Training was conducted, new manufacturing technology was benchmarked and tested, standards were reviewed, the concept was virtually and physically built, and the cross-functional roles were jointly discussed by product and production staff. The latter was considered a key benefit of the approach because of the degree to which it expedited development; one participant who was impressed by the resulting positive effects remarked, *"I am worried that this product will be industrialized sooner than X! [a product the participant had worked on previously]"*.[16] Project participants observed that the activities developed in Case II had never been developed at such an early stage previously and that the early development would reduce overall development times. Interestingly, during the project's early stages, efforts were made to maintain parity at the maturity levels of the products and production process.

In Case II, early phase work was seen as a way to operatively align advanced engineering from production with advanced engineering from technology and product portfolios. This, in turn, was seen as a way to integrate the development of the production systems and architecture processes, to achieve operations front-loading with the NPD, and to work towards production development for electromobility solutions.

Interestingly, product changes at the firm were classified as either (1) small changes, that is, variants using existing parts; (2) modifications of existing products; or (3) new products or major changes to existing products. However, there was no evidence that this classification was used in production-side design processes, for example, by considering the different changes in production work necessitated by the introduction of variants, product modifications, and new products/major changes.

The following section outlines the design process based on a theoretical framework that incorporates the key activities identified in the two cases, as well as the managerial and organizational characteristics of the projects.

5 An early-phase design process to enable long-term flexibility in assembly systems

As described in the preceding sections, the analysis revealed ways of working and activities that are beneficial for flexibility. However, a structured design process that supported design work was unavailable. Bellgran (1998) demonstrated that working systematically could accelerate the development of assembly systems and create better assembly systems. She proposed an assembly system-specific design process that suggested some fundamental principles relating to the content of individual process stages. As noted in the theoretical background section, Bellgran's work served as a basis for the development of the design process proposed in Fig. 3, which incorporates practices that support the creation of assembly systems with long-term flexibility.

Previous theoretical and industrial contributions have examined mechanisms for identifying approaches suitable for flexibility planning (Kampker et al. 2019a) and have highlighted the importance of early phases in the context of customization (Molitor et al. 2017; Rauch et al. 2019; Steimer et al. 2016). Based on the case studies presented in the preceding sections, we suggest that the design process of flexible assembly systems should be initiated concurrently with the early phases of technology development. As demonstrated, this is important for flexibility because it enables timely changes and adaptations of both product and assembly system designs. This helps in improving the alignment of product and assembly system lifecycles; for example the ability of a production equipment to accommodate product changes at an early stage in the development process can be examined (Vielhaber and Stoffels 2014). However, new production designs typically involve organizational and

[16] Production engineer, notes from a project meeting.

Research and Knowledge

Design process management		**Investment Request - Planning** Taylor the design process according to the change. For example, characterize the product-related change driver as: 1) small changes or variants using existing parts, 2) modifications to existing products, or 3) new products or major changes to existing products. Identify initial requirements/impact in assembly. Define the main purpose and scope, project main activities and outcome, proposal and deliverables, limitations, resources - cross functional (competence factor both from production and product as well as open for others), communication routines and project information sharing platform and meetings, project duration
Preparatory Design	**Background study**	**Mapping of the situation according to new product:** (Use complete 3D CAD Model, virtual tools and potential 1st prototype) **Situation Market** (Volumes, mix and delivery time) **Situation Product** Is the product modular? *Module content* - What are the modules and what parts are included in the modules (New parts and Modules? Carry over components?) - Product architecture *Assembly Sequence* - In what sequence are parts and modules assembled - Production architecture *Assembly Interfaces* How are parts and modules picked, moved, placed, and attached? (Evaluations of design criteria (such as pick points, direction positioning, easy access) as well as performance (ergonomics, safety, time, etc.)) **Situation Assembly** Assembly processes including equipment (existing processes, new process steps, new equipment? etc.) **Situation Purchasing and Material Handling** Suppliers of parts, and material handling (existing/new parts, number of parts, material handling solutions) **Bill Of Process and Materials**
Preparatory Design	**Pre-study**	**Specifying Vision and Objectives - Working with Scenarios** *What is the long-term vision?* Common product architecture and assembly sequence for electrical vehicles or should it be based on current common product architecture and assembly sequence of existing products? How do the new product and modules appear compared to the existing (commonality and functionality)? *Where should/will be the product produced?* Possible to group with another product? How does the assembly sequence look like there? What is the present situation of the products and assembly where the new product could be introduced? *How should assembly look like in the future?* Technology and Organization *What KPI´s should be met?* *Gap analysis between "wanted position" and current product, assembly and logistics* *Start discussing possible future models/variants of the new product to include in a common product architecture* *Benchmark* *Identify stakeholders and gather expectations and requirements*
Requirements and Expectations		**Requirements expectations from preparatory design - diverse stakeholders** For example, new competences considering new modules, processes, methods, new manufacturing technology Need of training - electrical safety, safety roles, and standards for electrical installation and handling of batteries Design Criteria, firm production system principles, logistic principles
Design Specification	**Design of conceptual assembly systems**	**Design Assembly and logistics Concepts - consider** Products design, size, weight Assembly sequence - commonality or possibilities to adapt Number of stations/zones Layout, available space for main assembly and subassembly and material presentation (easy to introduce or need to adapt) Product moving methods (common or need to adapt?) Work content – complete assembly times might not be available at this point for the new product but quantity of work allocated according to assembly sequence and material can be considered Commonality of parts and quantity of material Tooling/equipment, possible to use existing, or adapt or buy new? Assembly interfaces and commonality of processes - product criticism Organization/competence/roles
Design Specification	**Evaluation of conceptual assembly systems**	**Virtual Build** Prepare 3D material, animations, simulations /checklists to review (project decide the scope)/Define roles and responsibilities cross-functionally/documentation as well as follow-up Review of Product design/BOP/Sequence/Assembly Concepts Assess critical product changes (product criticism) and production deviations and possibilities for adaptation (e.g. by enablers) both for prototype building and serial production New modules, components, parts, process, systems Tooling/Equipment Logistics Operator training needs Safety/Ergonomics Quality, PFMEA review, etc.
		Physical Build/ Proof-of-Concept Test the assembly, logistics concepts and product design changes while building the prototype Film and gather assembly times and continue development of assembly instructions based on 3D material Evaluate: Assembly sequence Product moving method Manufacturing technology Safety/Ergonomics/Complexity Assembly interfaces Material Handling Get continual feedback from Operators Pilot test of product in customer setting
Design Specification	**Detailed conceptual design of assembly system**	**Detailed Design** Design detailed concepts based on different volume scenarios Compare production architectures Evaluate balance Evaluate cost for serial production Simulation Assess Manufacturing readiness level and get input from Technology readiness level (Assess parity between them) Define requirements for NPD

Fig. 3 An early phase design process enabling long term flexibility in assembly systems

technological changes (Reichstein and Salter 2006). Therefore, it is beneficial to identify new roles or competences that may need to be established or acquired through training and education. New organizational arrangements with suppliers may also be needed, as demonstrated in the case studies. In addition, possible variants and future platforms were discussed in Case II, and the resulting information was included in the interface diagrams. This provided valuable initial guidance on possible changes in product size, which in turn influenced the design of production stations/zones and their layouts. Therefore, the early interaction between product and production design guided the decision-making process concerning flexibility, which is known to be challenging because of the unknowable nature of future production scenarios (Abele et al. 2006). The proposed process is presented in Fig. 3 and its individual phases are discussed below.

5.1 Project initiation–design process management

Reactive process development and ad-hoc documentation are some of the characteristics of front-end projects (Kurkkio et al. 2011). These problems can be mitigated by appropriate planning and management of design processes. A formal design-process management phase, including planning, was considered crucial in the studied cases. This was partly because the firm needed to establish a shared understanding between product and production (Case II) by defining the project description and investment requests, common activities, main objectives, roles involved, scope, and so on. Securing funds (for both product and assembly system design) and time is recommended to support parallel and integrated design processes. Multiple scholars have discussed the importance of planning and coordinating activities that synchronize the individual plans in the design and development processes (Bellgran 1998; De Lessio et al. 2019; Eckert and Clarkson 2010). However, informal discussions before formal commencement are also important for establishing a consensus about the project and, as noted by Kurkkio et al. (2011), for generating and refining ideas, as in Case II, for example, about the new product.

It should also be noted that, although formalization of the projects was desired, development projects should have an internal organization that supports knowledge sharing and learning to achieve the project objectives. Approaches that incorporate self-organizing project teams, organizational transfer of learning, and overlapping development phases are beneficial in this respect (Molitor et al. 2017; Takeuchi and Nonaka 1986). The case studies showed that a stable project team was necessary; however, recognizing that other supporting functions are needed during the design processes and establishing appropriate communications between individuals with different responsibilities and effective information-sharing platforms are also important. Crucial roles during project initiation include project managers from both the product and production sides; individuals responsible for product, production, and material handling architecture; product designers and production engineers (designers); purchasing personnel; logistics and material handling developers; simulation and virtual tools experts; product and production researchers; individuals responsible for prototyping; operators from assembly and logistics; and individuals with expertise in safety and ergonomics. Individuals with knowledge of flexibility and reconfigurability, who can provide support for these issues, should be included as well. Important reference group members and representatives of supportive functions include test area/factory managers, design tooling, maintenance, fabrication, production system personnel, automation/system experts, and production preparation/planning staff. Collaboration or agreements with suppliers and consultants may also be needed to ensure an adequate supply of materials and solve specific problems, respectively. The involvement of customers may be required for developing and testing products according to the customer needs. In addition, the involvement of a process planning manager/director is important to assess experiences, provide support, and systematize the work to improve other design processes at the firm.

Previous studies on NPD and traditional stage-gate models have shown that design processes should be context-based and scalable (Cooper 2019), which implies that no model can fit all projects (Wynn and Clarkson 2018). Thus, the organization of the design process should be tailored to the desired change. As noted previously, product innovations such as electric vehicles can necessitate radical innovations during the early stages of diffusion and adoption as well as incremental innovations during the advanced stages of the product's life cycle (García and Calantone 2002). The firm studied here classifies products as either (1) small changes or variants using existing parts, (2) modifications to existing products, or (3) new products or major changes to existing products. However, this classification was not adopted in production-side design processes, which is important because factors such as the degree of novelty, state of existing knowledge, sources of ideas for process development, and scope of the process development project could significantly affect the organization of the design processes (Kurkkio et al. 2011). These classifications correspond to different types of flexibility, namely mix, modification, and new product flexibility, and supporting flexibilities (Svensson Harari et al. 2014). Therefore, understanding the degree of change that a new product represents is important in assembly system design processes. Studies suggest that the adoption of process models that are suited to its exploratory nature and the uncertainty of development work, if used flexibly, can facilitate technology development (Högman 2011).

5.2 Preparatory design

According to Bellgran (1998), the preparatory phase encompasses background study ("looking back") and pre-study ("looking ahead") and is conducted with the aim of specifying requirements that state "what should be achieved". However, these phases are not strictly sequential and can be performed in parallel and iteratively. A key goal of this phase is to determine the mapping of a new product to the current production setup. Kurkkio et al. (2011) suggested conducting literature reviews and reported that the changes in the end product could be anticipated during the formal idea-study phases. Notably, the production research personnel participated extensively in the studied cases and conducted the literature reviews. The availability of complete 3D CAD models was critical during this phase in Case II because they allowed the product to be understood and visualized, assisted the gathering of product information, and enabled the generation of instructions, assembly sequences, bills of process, and bills of materials.

An overview of the market situation must also be acquired during the preparatory design phase because it provides an idea of likely production volumes, delivery times, and possible product mixes. In addition, this requires an analysis of the product, assembly systems, and material handling procedures, both currently and in the future. Decisions regarding the architecture and modules of both the products and the assembly system are important in this context, along with issues relating to material handling, such as commonality of parts. Therefore, product modules, assembly sequences, assembly interfaces, assembly processes, equipment, purchasing, and material handling must be analyzed. Common assembly interface assessments, such as gripping, setting, and tooling, and common assembly sequence analysis can increase the flexibility in assembly (Lafou et al. 2016a, 2016b). However, it is not usually mentioned in the context of the design processes of flexible assembly systems. In Case II, the interfaces were assessed from an assembly perspective to enable common operating methods, such as picking, moving, placing, and attaching. Co-developing products and assembly systems simultaneously (Abbas and ElMaraghy 2018; Michaelis 2013) is also beneficial in addressing this aspect, as are decisions connecting the market to product and production architectures (Mortensen et al. 2011). Thus, determining the level of modularity needed to achieve adaptability is beneficial for the system life cycle (Engel and Reich 2015) and can be determined at an early stage during the design process (Engel et al. 2017). This should occur in a cross-domain fashion: it should encompass both technical and non-technical aspects. Other important tasks in the preparatory design phase are defining key performance indicators, analyzing the gaps between the current situation and the "wanted position," including possible future product variants, benchmarking, and clarifying requirements.

5.3 Design specification

The design specifications in the early phase, as shown in Fig. 1, encompass conceptual design and evaluation. The evaluation results provide valuable input for a more detailed conceptual design. The concepts can be developed using the current situation, wanted position, expectations, and requirements. The analysis of the products to be grouped and the assembly sequence can guide this work to decide on assembly stations or zones, layout, etc. While various dimensions of flexibility have been discussed in the literature, the case studies revealed specific examples of flexibility that were considered during the assembly system design process. Because a flexible assembly system has some level of reconfigurability at both individual and groups of workstations (Kampker et al. 2019a; Wiendahl and Heger 2004), reconfigurability must be considered during the design process. Decisions must strike a balance between achieving commonality, standardization, adaptation, and the integration of new components. In Case I, a flat assembly base was adopted, along with a generic approach that allowed easy and fast configuration for handling products of different sizes and weights. Another major issue that emerged during the studied cases was the need for standardized equipment for all products manufactured in a given assembly arena, while also ensuring that the assembly zones and equipment are adaptable and reconfigurable to accommodate new products or product mixes. Both these factors contribute significantly to flexibility.

Evaluation and testing are crucial in design processes to ensure compliance with requirements, enable participants to learn about design and understand new technology, and obtain feedback from stakeholders regarding emerging designs. Additionally, they can provide support in situations that are difficult to express and/or formalize as technical requirements (Tahera et al. 2019). This is particularly relevant, given the complexity that can result from efforts to achieve flexibility. The difficulty of defining change requirements has been discussed in the literature, clearly showing that evaluations are important at multiple stages in the design process: before the change, during the selection of the solution, and after implementing the change (Bellgran and Säfsten 2010). Both projects involved virtual and physical evaluations. In Case II, the assembly concept was discussed virtually and then built physically during the course of design work. This allowed, for example, the testing of the assembly sequence and estimating the assembly times for a more detailed conceptual design. In Case I, methods were developed to evaluate factors such as the ability of the assembly interfaces to pick, place, and attach. Complexity was also considered in Case I based on the increased number of variants and its possible impact on assembly. Analyses of complexity from operators' perspectives have revealed concerns about work variance and workstation design in automotive companies (Tarrar et al. 2016). The work environment is crucial in both the design and evaluation of different concepts and should be considered in the early phases of design processes for flexible assembly systems.

The involvement of different roles and functions, ranging from managers to system users, has a significant impact on the design and results. In particular, the participation of the production operators was crucial. This shows that, as predicted by theory, the incorporation of diverse perspectives has a significant impact on projects (Reich 2008). A holistic approach and an integrated multidisciplinary design supporting different disciplines to avoid failures are justified (Abdoli and Kara 2019). Participation is particularly important to flexibility. As noted above, flexibility has several distinct dimensions (Koste and Malhotra 1999) and is associated with many differences in interpretations, interests (Allvin and Aronsson 2013), and perspectives (D'Souza and Williams 2000). All of these issues should be discussed and evaluated during projects. In addition to defining flexibility, the projects established connections with the different components of the system. For example, the product characteristics and assembly sequence were linked to the production layout, number of stations, balance, equipment, organization, available space, and material handling.

Technology development is characterized by the creation of skills, knowledge, and artifacts (Högman 2011). However, knowledge management must also be considered to avoid rework of activities, which can increase redesign costs and lead to ineffective responses to fast change requests (Reich 2008). Appropriate tools and techniques should be used to facilitate the participation and gathering of different perspectives (Broms 2009), such as mock-up models (Österman et al. 2016). A wide variety of tools were used for this purpose in the cases, including simulations, proof-of-concepts, product and assembly system prototypes, virtual buildings, CAD product models, 3D illustrations, animations, architecture diagrams, and training in electrical safety. They enabled concept development, the creation of assembly instructions, and discussions about assembly sequences, safety, and ergonomics, which generated adaptations and changes in products and assembly. The combined use of prototypes and digitalization tools to support assembly system design was found to be advantageous. The literature show that such tools could be beneficial, for example, simulations performed by experienced workers using prototypes and computer manikin analyses that enable the re-design of new products, improving efficiency, and the ergonomics of assembly during early phases (Sundin et al. 2004). In addition to the potential advantages of participatory approaches in terms of production performance, other benefits of involving personnel during the early phases include the possibility of expanding available knowledge, contributing to acceptance (Kadefors 2009), learning (Österman et al. 2016), and reduced uncertainty (Sjödin et al. 2016). The concept and evaluations provide inputs for a detailed conceptual design; the activities are specified in Fig. 3. The extent a design can be detailed at this stage can be debated; however, at the end, the readiness levels and maturity of the technology and manufacturing are assessed to find some alignment and achieve some parity in the development of the product and assembly systems. Finally, research also played a notable role. Although research on production is rarely mentioned in the literature on design processes for assembly systems, connections to research have been found to be beneficial in all phases of innovation processes, including production (Kline and Rosenberg 2009). Production research was an important part of the two projects considered here.

Finally, the design process presented here is not only connected to technology development processes, but also to architecture processes and the integration of new manufacturing technology processes. As mentioned, when discussing Case II, this could also be achieved by aligning AE operations with AE technology, products, and production system portfolios to operatively integrate the design process of products with assembly systems. This could be particularly beneficial when seeking long-term flexibility. Although Case I established multiple ways of achieving flexibility and enablers, the realization of the solutions was difficult because they were identified a long time after the product designs had been finalized. This hindered the implementations of the changes and adaptations. However, this can be avoided by coordinating the early-phase work and involving predictive analysis of different production development scenarios; this was highlighted in Case II. Similarly, Kurkkio et al. (2011) found that activities such as anticipation of end-product changes and modification of process equipment were critical in the early phases. In addition, as shown in the cases, the organizational aspects are crucial for design work with a long-term perspective and the corresponding results. In this regard, some important aspects to consider include a proactive preparation to the changes, the management of the design work, the participation, and involvement of different roles and functions from products and production systems with various competences, which would also enable a holistic perspective, training and education of the personnel, and the learning of the organization.

6 Conclusions, managerial implications, limitations and future research

The following section summarizes the conclusions, managerial implications, limitations, and future research.

6.1 Conclusions

The need for further research on the early phases of production development has been previously highlighted (Lager 2002; Lim et al. 2006; Pisano 1996), with particular emphasis on the knowledge gap relating to early phases and activities (Frishammar et al. 2013; Kurkkio et al. 2011). This issue was initially raised in the context of the process industry. However, it is also important in the manufacturing industry given the rising demand for flexibility to accommodate product variety, shorter product life cycles, and the transport sector's transition towards radical product designs, such as those for electromobility systems. Therefore, iteration and integration of product and production design processes should be given particular attention during the early phases (Steimer et al. 2016; Vielhaber and Stoffels 2014). In general, the consensus in the literature is that late changes in product realization processes are costlier than early changes (Bellgran and Säfsten 2010; Eder 1998; Reich 2008) and that sequential approaches can give rise to design inconsistencies (Abdoli and Kara 2019). However, research on the potential of enhancing flexibility during the early phases of design processes for long-term solutions is limited. Therefore, the work presented here aimed to expand the knowledge in this area.

While the theoretical framework defined phases and highlighted some activities that can be beneficial in the early phases of design processes for assembly systems (for instance, the phases proposed by (Bellgran 1998)), this study incorporated findings based on deep empirical evidence analysis, illustrated the importance of integrating the assembly system design process with the early phases of technology development, and specified activities related to flexibility. From a design process perspective, this indicates the importance of addressing the iteration of these processes in tandem with that of other key processes within the firm, rather than treating them as isolated processes (Gericke and Blessing 2012). In this sense, the design process presented here is not only connected to technology development processes but also to architecture processes and the integration of new manufacturing technology processes. As mentioned before, this could also be achieved by aligning AE operations with AE technology and product portfolios and integrating the design process of products with that of assembly systems. This could be especially beneficial when seeking long-term flexibility because while Case I established multiple ways of working towards flexibility, the realization of the solutions was hindered by the fact that they were identified long after the product design information had been finalized, which rendered changes and adaptations arduous to implement. This can be avoided by coordinating early phase work and involving the predictive analysis of different production development scenarios. Similarly, Kurkkio et al. (2011) found that activities such as anticipation of end-product changes and modification of process equipment were critical in the early phases.

6.2 Managerial implications

To support the transition to electromobility and ensure survival in the current volatile market situation, firms should establish guidelines for active and well-coordinated product and production design. Design processes are crucial for this and should be structured so that they are consistent with the desired outcomes. The design process presented here is based on experiences gathered during two projects in a global firm that revealed activities and ways of working to enhance flexibility in design processes related to electromobility. The advantage of drawing on project experience during process development has been discussed previously (Bellgran and Säfsten 2010).

Addressing flexibility during design is challenging both theoretically and practically. However, the alternative of working in an ad hoc manner with isolated processes and plans that focus exclusively on technical solutions is not viable and leads to poor outcomes. Development projects cannot be managed as they have been in the past, and new techniques are needed that incorporate knowledge management, research, the involvement of co-workers, new organizational structures, and collaboration with other actors from academia, suppliers, customers, and research institutes. The number of stakeholders has increased significantly. Conducting a greater proportion of production design work during the early phases of product development, integrating design processes, and using participative approaches that include diverse stakeholders appear to be important in this context.

Finding mechanisms to align cross-domain architectural decisions is also relevant. The number of prototypes built in Case II was unusually high (seven). Together with the integration of research and customer participation, this increased the project depth and represented a new approach for the firm and its business model. Such prototyping and integration should be considered in future projects.

6.3 Limitations and future research

The presented design process incorporates working procedures and activities that enable flexibility in the studied context, and the analysis on which the process is based indicates that early phase work is particularly important for achieving flexibility in both products and assembly systems. However, this work has some limitations that should be noted. First, both case studies were conducted in a single company, which limits the external validity of the results and conclusions to some extent. However, this approach also had strengths; in particular, it allowed data to be collected in real time and thus eliminated the risk of respondents misremembering past events (Eisenhardt and Graebner 2007) and provided in-depth empirical saturation and evidence.

Notably, the assembly and product design processes at other firms producing different products may differ markedly from those studied here. Therefore, additional studies are required to assess the transferability of the approach presented in this study. Several areas have been identified for future work, such as the impact of product change classification on the design processes of flexible assembly systems. The interconnections between product flexibility design and flexible assembly system design processes seem worthy of investigation. Therefore, future studies could investigate the coordination of design decisions between the product architecture, production, and supply chain domains (Fixson 2005) and the impact of modularity decisions (Engel et al. 2017) on flexibility. The role of smart engineering design in relation to changeability and modularity, as well as fourth industrial revolution practices such as continuous engineering and the adoption of model-based system engineering (Pessôa and Becker 2020) also warrant further study. Finally, the results presented by Eckert et al. (2019) suggested that product development processes would be less prescriptive in the future and more reliant on the involvement and integration of disciplines, teams, and collaboration. An increased use of advanced technologies, such as AI systems and robots, and the use of digital representations are also expected. The simultaneous design of products and assembly systems using these methods and tools should be investigated with respect to the design processes of flexible assembly systems.

Appendix 1

Overview of the case studies and data collection

Study	Technique	No./Period/Duration/Design Phases	Type of data collected
Case study I	• Active participant observation in project activities, including weekly project meetings and workshops (This included development of concepts in assembly and logistics, methods, design procedures, etc.)	More than 300, from Sept 2012 to May 2016	Project organization, context, way of working, design process, activities, challenges, design characteristics, solutions, flexibility, activities about simulation, assembly modules, interfaces, product architecture, development concepts both assembly and logistics and design procedures
	• Templates Product	12 main products and 97 variants	Product family and variants, dimensions, weight, drawings
	• Templates Assembly Systems • Consultation and conversation with each assembly responsible • Direct consultation and conversation with assembly operators in each of the stations of each of the assembly line in two factories	11 assembly lines Participating Factories (Several assembly lines in each factory) 3 Sweden, 1 Poland, 1 USA, 1 South Korea, 1 France, 1 Germany	Layout drawings with dimensions, number of stations, assembly times, number of operators, critical processes, differences in processes, pictures, specific equipment, subassemblies, material handling system information
	• Direct participative observations This also included the opportunity to try/perform some of the assembly processes, such as the cab module assembly in a final product	5 of the participating factories	Flexible assembly and logistics including challenges and enablers

Study	Technique	No./Period/Duration/Design Phases	Type of data collected
	• Questionnaire Logistics • Conformation of global logistics reference group	6 from Sweden, Brazil, South Korea, USA, Poland, and Germany	Material handling system including: block layout of material flow, procurement principles, inventory, line feeding, material presentation, use of ICT technologies, kitting, etc
	• Face to face semi-structured interviews completed via skype • Face to face semi-structured interview (recorded, transcripts organized in a predefined interview template of knowledge and in view of the interviewed people. Categories of challenges came both from theory contrasted with feedback from key informants of the firm who were asked for input)	1 Assembly project coordinator/investments/Layout (289 min) 1 Logistics responsible and developer (135 min) One main factory on the way to develop a flexible assembly system	Overview of the assembly and products. Challenges and enablers in assembly and logistics for the design process of flexible assembly, possible solutions and functions in charge of the solution Presentations about logistics strategy, line feed methods, assembly hall
	• Study visits including meetings, participative observations in the assembly lines and logistics Non-direct participating factories in the project	2 One in Sweden and another in Brazil, working towards mixed-product assembly	Design process work and flexibility
	• Benchmark activities	4 external of the automotive sector 1 Internal	Flexible assembly and logistics including challenges and enablers
	• Meeting with a material handling supplier together with logistics developer and operators from assembly and logistics	1 in the suppliers workshop	Flexible material handling solutions and development of prototypes (tested afterwards)
	• Application of Complexity Index CXI (Mattsson et al. 2016) to give input to the project	93 operators assembly 18 operators logistics 4 workshops	Perceived complexity and feedback from workshops – results discussion
	• Document studies	Full access	Project documentation including presentations, reports, photos, etc. Company documents about production systems, project models, etc
	Continual consultation• and conversations with key informants with different roles and functions in several factories	All the design process phases	Wide range, e.g. about design processes and flexibility
	• Notes	All the design process phases	Reflections after meetings, consultations, etc
Case study II	• Active participant observations in the project activities, including project meetings and workshops (This includes product designers and purchasing meetings as well as main research project meetings)	More than 100, from May 2017–Feb 2019	Project organization, context, way of working, design process, activities, challenges, design characteristics, solutions, flexibility
	• Study and analysis of product data from CAD model	Several–all the design process phases	Product information, modules, components, parts
	• Meetings and workshop with Product architecture expert as well as with product expert and assembly responsible	All the design process phases	Knowledge on how to work with architecture, guidance, and definition about appropriate level to work in the project. Support to activity below
	• Active participation in the elaboration and review of product and production architecture diagrams together with product architecture expert, product expert, assembly responsible and development operators. Study and analysis of the results	All the design process phases	Product components and modules information as well as corresponding interfaces. Production structure, sequence, main assembly, subassemblies, etc. 1 Product Diagram 1 Production Diagram
	• Active participation in the elaboration and review of assembly sequence with assembly responsible	All the design process phases	Assembly sequence, main assembly and subassemblies

Study	Technique	No./Period/Duration/Design Phases	Type of data collected
	• Support in planning and direct observation of virtual build with ~ 19 participants: Assembly responsible, production engineer, development workshop manager, process director, 3D images expert, logistics personnel, 4 assembly development operators, 3 product design experts, 1 system expert, electrical systems experts, and chief project manager	2 Days virtual build	1 compendium with 3D pictures and topics to be reviewed. Pictures and records Product criticism and production deviations as well as discussions about assembly sequence, new manufacturing technology, tools, fixtures or adaptation, assembly methods, safety, ergonomics, etc
	• Study and support in logistics concept development	From Sept 2017–Feb 2019	Logistics concept, number of parts, commonality, material presentation, etc
	• Study and support to generation of assembly instructions	During preparatory design and design specification 1 compendium by station	Assembly sequence, main assembly, subassembly
	• Study of the safety evaluation documents. This includes a meeting with safety responsible, assembly responsible and maintenance	Before, during and after physical build/proof-of-concept	Safety issues, standards
	• Study, and assessment analysis of assembly modules and interfaces	All the design process phases	Assembly modules and interfaces from assembly perspective
	• Active participation in the elaboration and evaluation of assembly system prototyping concept	All the design process phases	Assembly sequence, main assembly, subassembly, new components compared to existing and functionality, material handling, new manufacturing technology
	• Direct observations of prototyping development work both for product and assembly system	All the design process phases	Product changes, assembly sequence, process
	• Workshop presentation of on-going results. Approx. 50 people attended from junior employees to senior management, representing a variety of functions within the firm including Product design, Production, Marketing and Product Portfolio and Sales. In addition to this, representatives from the customer company have collaborated with on the main research project – were also in attendance as well as one Academic supervisor	During physical build/proof-of-concept 1 workshop / 2 seminars	Feedback about on-going work
	• Active participation in the elaboration of the assembly systems concepts integrating (current products and new product)	During design specification—3 scenarios	Design process, parameters to take into consideration from flexibility point of view
	• Study of electrical standards	2 standards	Electrical installations and handling of batteries
	• Training in electrical safety	2 separate training sessions	2 electrical roles approved, one concerning Develop tools and equipment, write instructions and procedures and risk assess new electrical work
	• Direct observation of product test in customer facilities	During evaluation of prototypes 1 day	Customer process, working cycle, charging station, control stations, systems, maturity of the technology, status of the tests, challenges, etc
	• Co-development of manufacturing readiness level assessment	During final stages of design specification. Compiled in 1 document	Steps towards SOP
	• Document studies	Full access	Project documentation including presentations, reports, photos, films, etc. Company documents about production systems, project models, etc
	• Continual consultation and conversations with key informants with different roles and functions of the firm	All the design process phases	Wide range, e.g. about product and production design processes and flexibility
	• Notes	All the design process phases	Reflections after meetings, consultations, etc

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