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Using Business Critical Design Rules to Frame New Architecture Introduction in Multi-Architecture Portfolios

When introducing new architectures to an industrial portfolio, counting multiple existing product and manufacturing solutions, time-to-market and investments in manufacturing equipment can be significantly reduced if new concepts are aligned with the existing portfolio. This can be done through component sharing, or sharing critical design principles. This alignment is not trivial, as extensive design knowledge is needed to overview a portfolio with many, often highly different products and manufacturing lines. In this paper, we suggest establishing a frame of reference for new-product introduction based on several 'game rules', or Business Critical Design Rules (BCDRs), which denote the most critical features of the product and manufacturing architectures, and should be considered an obligatory reference for design when introducing new architectures. BCDRs are derived from the portfolio, architecture and module levels, including modelling of the most critical links between the product and manufacturing domains. The suggested modelling principle has been tested as a frame for new-architecture introduction, capturing critical modularisation principles in a large and global OEM. Application of the suggested method revealed a potential for reducing time-to-market and potentially cutting 35% off investments in new manufacturing equipment when introducing new products in the portfolio.

Keywords: product platform, portfolio management, cost improvement, new-product development, architecture introduction, design rules

1. Introduction

In a competitive global market dominated by heterogeneous customer demands and short product-life cycles, industrial organisations are seen developing product families based on shared platforms and architectures (Simpson et al. 2014). This potentially can elicit fast and cost-efficient introduction of new products, as development need not start from zero every time a project is launched (Meyer and Lehnerd 1997). Embedding a level of modularity into the architecture of a system is generally accepted as a way to reduce time-to-market and increase flexibility toward variant creation (Mikkola 2006). The approach focuses on minimising dependencies within systems to allow for parallel development facilitated through interface standardisation and reuse of design principles (Baldwin and Clark 1997). Much research effort has been focused on supporting organisations in designing modular product architectures and platforms. This includes design support across the life cycle of the product and across domains, i.e., market, product, manufacturing and supply chain (Fixson 2005; Carrillo and Franza 2006; Kubota, Hsuan and Cauchick-Miguel 2016). However, sharing architectural characteristics, common platforms and modularisation principles across an industrial portfolio demands a level of governance to successfully harvest the benefits, and organisations have failed at such efforts (Sanchez 2013). This is especially difficult with industrial portfolios containing multiple product and manufacturing architectures, as extensive design knowledge is needed to fully understand the implications of introducing new products or product variants (Schuh et al. 2016). Creating an overview of existing architectures across an industrial portfolio, as a reference for concept development can be beneficial by allowing for assessment of concept compliance with existing architectures, strategic decisions related to modularisation, and the use of platforms (Jiao, Simpson and Siddique 2007; Gudlagsson et al. 2016). However, modelling characteristics for multiple architectures have had limited focus, and operational methods that can describe high-level and critical architectural characteristics across product lines, architectures and domains are lacking. In this paper, we propose the mapping of Business Critical Design Rules (BCDRs) to encapsulate these critical characteristics. The proposed framework adds to literature on how to model and operationally describe the most important characteristics of product and manufacturing architecture. This makes it considerably easier to communicate important decisions on modularisation and improve the ability to make decisions at the portfolio level. The case study indicates that identification and modelling of BCDRs lead to improved decision making when designing products and factories, which, in turn, can lead to significant improvements in manufacturing-capacity utilisation, resulting in potential investment reductions of up to 35%.

The following sections describe the basis for the suggested framework. First, the concepts and characteristics of architectures and platforms are introduced, followed by a description of how links are established across domains. Finally, existing methods for describing and modelling multi-architectures are discussed before introducing the suggested principle for modelling BCDRs.

1.1. Product architectures and platforms

A product architecture is a carrier of structural and functional design decisions (Fixson 2005; Gudlaugsson et al. 2014) and is an essential enabler for modularisation and platform application (Simpson et al. 2014). Ulrich (1995) generally defines a product architecture as the arrangement of functional elements, the mapping from functional elements to physical components and the specification of the interfaces among interacting physical components. Sharing product architectures and standardisation of interfaces can be seen as the basis for product-family design, i.e., products with similar structures and a level of commonality between variants (Harlou 2006). While the architecture represents the structural and functional decomposition of a product, a product platform can describe the collection of modules, or parts, from which specific products can be derived and efficiently launched (Meyer and Lehnerd 1997). Robertson and Ulrich (1998) expand this definition to describe a collection of components, processes, knowledge and people and relationships shared by a set of products. Modelling BCDRs is based on the understanding that a product architecture defines the basis for product family design and can be seen as a rule-based scheme capturing the most important design knowledge. The platform can be seen as a collection of critical assets shared across product families or product variants (Ostrosi et al. 2014; Parslov and Mortensen 2015).

1.2. Manufacturing architectures and platforms

Like the product domain, a manufacturing system can be seen as a structural combination of subsystems, together performing a complex function (Mesa et al. 2014; Jepsen 2014; Gudlaugsson et al. 2016). Both systems exhibit characteristics as a result of design choices, and the value-adding processes performed by the manufacturing system can be seen as corresponding to the functions of a product (Claesson 2006). As in the product domain, it is possible to describe and model a manufacturing architecture capable of capturing critical structural and functional design knowledge. Furthermore, it is possible to embed modular characteristics by decoupling dependencies between subsystems (Jiao, Simpson and Siddique 2007; Mesa et al. 2014). Building modularity into the architecture of a manufacturing system generally has been found to enable reduction of setup and lead time, increased system flexibility, cost reductions, easy replacement of defective modules and quality improvements (Rogers and Bottachi 1997; Piran et. al. 2016). In this paper, we build on the understanding that manufacturing architectures and product architectures can be represented in similar ways that capture important design knowledge.

1.3. Linking architectures across domains

Product architectures and related manufacturing architectures can be, more or less, closely linked (Carrillo and Franza 2006). Designing modularity into a product architecture for easy assembly creates an intuitive link between the two domains, and the level of modularity embedded in a product architecture can be seen as affecting the modularity of the manufacturing system, such as in relation to outsourcing decisions, production layout and product-variant creation (ElMaraghy and AlGeddawy 2014). Designing modularity into a manufacturing architecture can affect the product architecture, e.g., through co-design efforts with suppliers or through standardisation of value-adding processes (Kubota, Hsuan and Cauchick-Miguel 2016). Understanding links across the two domains is important for efficient and fast introduction of new products (Carrillo and Franza 2006). ElMaraghy and AlGeddawy (2014) describe how the product, manufacturing and market domains interact and develop over time as a biological co-evolution. In their Associated Product Family Design (APFD) model, they relate requirements and constraints at the architectural level and across market, product and process domains to support the design of modules, platforms and process plans. The APFD can be used to link the product's architectural characteristics to the 'master assembly process plan' for all variants in a product family, as well as to the physical layout of assembly processes. Jiao, Zhang and Pokharel (2007) introduce the Generic Product and Process Structure (GPPS) as a tool for coordinating product and process variety. The GPPS can be seen as a meta-structure and reference, from which several product and process variants can be derived. Material requirements link the process and product domains. Also, Design Structure Matrices (DSMs) and variants of these (Eppinger and Browning 2012) are used to establish relationships between domains and highlight important architectural characteristics (Baldwin and Clark 2000; Browning 2016). DSM terminology has been applied to link product domains to several associated domains, including manufacturing, through what Danilovic and Browning (2007) define as a Domain Mapping matrix (DMM). Modelling critical architectural relationships across the product and manufacturing domain is considered a key element of the proposed framework. The modelling principle applied is based on the understanding that product and manufacturing architectures can be described in similar ways, and links can be established across functional and structural elements in the two domains.

1.4. Describing characteristics of multiple architectures

Leveraging from modular architectures and platforms as a strategy for new-product development demands managing design knowledge on the standardisation of interfaces, platform assets and strategic drivers (Campagnolo and Camuffo 2010; Simpson et al. 2014).

Even with the potential to largely impact portfolio management (Mikkola 2001), capturing this knowledge across a portfolio containing multiple product and manufacturing architectures has received little research attention. Assessments related to the introduction of new architectures into a portfolio focus mainly on optimisation of portfolio profitability (Cooper, Edgett and Kleinschmidt 2001), resources (Danilovic and Browning 2007; Dash, Gajanand and Narendran 2017) or market-strategic drivers and constraints (Ghaemzadeh and Archer 2000). The level of commonality among product variants also can be used as an evaluation metric in deciding product launches (Tucker and Kim 2009). Some contributions seek to expand the perspective of modularisation and platform development, to become a guiding factor in portfolio management by, for example, introducing the concept of Design Bandwidth (DB), which relates to a platform's ability to accommodate existing or future product designs in terms of functionality, performance and variants. DB can be expressed in relation to functional requirements, design solutions and constraints (Berglun and Claesson 2005; Michaelis and Levandowski 2013). High bandwidth means that a platform has a high flexibility to accommodate various new products. Defining DB enables continuous evaluation of new concepts against the platform. Baldwin and Clark (2000) introduce what they call hidden and visible design rules to capture high-level decisions related to a modularisation strategy. The rules are hierarchical design parameters relating to system architecture and are a way of capturing strategic decisions and supporting modular development. The application of Modular Function Deployment's (MFD) module drivers (Östgren 1994; Erixon 1998) is another approach to linking business-strategy aspects to product architecture and to modularisation efforts. Module drivers include 12 perspectives and can allow for embedding strategic considerations related to definition, application and life-cycle aspects of modules in product architectures (Lange and Imsdahl 2014). A Module Indication Matrix (MIM) can be used to link a modularisation strategy, based on the module drivers, to specific components or subsystems of a product architecture. The PKT-Approach (Krause, Eilmus and Jonas 2013), which includes a perspective on the product program, embeds product family development in a corporate strategy. The Product Structuring Model (PSM) divides the product portfolio into five levels: product program, production program, product lines, product families and products. Combined with the Carryover Assignment Plan (CAP), sharing and carryover potentials across the product program and generations of product families can be visualised. Borjesson and Hölttä-Otto (2014) present an algorithm based on integration of a DSM and MFD/MIM, allowing for a strategy for product commonality to be balanced with module independence. The approach is a way to integrate strategic portfolio drivers and capture company component sharing or modularisation strategies in the development of modular product architectures. DSM-based approaches are widely used for mapping system relations and relations across domains. However, a challenge is that when looking across multiple architectures and multiple domains the complexity of the matrices grows to a level where they become difficult to handle, and difficult to use as basis for communicating key architectural characteristics in daily design processes. Generally, several aspects of multi-architecture modelling are supported by existing methods, including sharing of platform assets and the integration of strategic drivers. Support is, however, limited when it comes to capturing characteristics across multiple architectures and operationally communicating these.

1.5. Summary and research opportunities

Several review papers on the topic of modularisation as a strategy created the basis for our understanding of challenges related to operationalization of the concept. Relevant contributions are summarised in Table 1.

Table 1. Overview of review papers

Reviews of related literature	Research focus	Relevant conclusions
Jiao et al. (2007)	Review of product family and platform-based product development. (Based on 246 references)	• Need for holistic and system-wide solutions in relation to product family design. • Need for coherent framwork including front-end issues: Customer integration, market segmentation and economic evaluation, and back-end issues: Manufacturing and supply chain considerations.
Campagnolo and Camuffo (2010)	Review of modularity in management studies. (Based on 125 references.)	• Need for all-around framework bringing light to relatioships between product, production and organisational modularisation • Need for studying cost of developing modular product architectures
Bonvoisin et al. (2016)	Review of modular product design. (Based on 163 references)	• Need to defin modularisation metrics to achieve a leveliof defintion that is practical enough for engineers. • Research is needed to embed principles of modularisation in day-to-day design activities.
Piran et al. (2016)	Review of modularisation strategy in production and operations management. (Based on 81 references.)	• Need for studying background for modularity in production • Need for quantifying effects of modularisation
ElMaraghy et al. (2013)	Review of product variety management. (Based on 224 references)	• Need to improve communication among stakeholders in the product life cycle to link commonality assessment to the structure of the product architecture. • Need for integrating "design for variety" with manufacturing system synthesis and design.

Common elements were identified as: (1) a need to improve the understanding of relationships between product architecture and manufacturing architecture, and (2) a need to improve communication of architectural characteristics and relationships, to better support embedding modularisation principles in the development of new products and manufacturing systems. Practical screening of literature from the review papers and a backward reference search led to several papers focusing on definitions and modelling principles of architecture characteristics. These create the theoretical basis for the proposed framework for modelling BCDRs. Table 2 provides an overview of key literature and constructs linked to modelling principles.

Table 2. List of relevant papers describing architecture characteristics

Relevant papers:	Main focus on product architecture characteristics	Main focus on manufacturing architecture characteristics	Perspectives of product family design	Cross-portfolio perspectives applied
Albers et al. (2015)	x		x	
Baldwin & Clark (1997)	x		x	
Baldwin & Clark (2000)	x	x	x	
Berglund & Claesson (2005)	x		x	x
Borjesson & Hölttä-Otto (2014)	x		x	x
Brunn et al. (2014)	x		x	
Claesson (2006)	x	x	x	x
Danilovic & Browning (2007)	x		x	
ElMaraghy & AlGed-dawy (2014)	x	x	x	
Eppinger & Browning (2012)	x		x	
Erixon (1998)	x		x	
Fixson (2005)	x	x	x	x
Gudlaugsson et al. (2014)	x		x	
Gudlaugsson et al. (2016)	x	x	x	
Harlou (2006)	x		x	
Hsuan & Hansen (2007)	x			x
Jepsen (2014)		x	x	
Jiao et al (2007)	x	x	x	
Koren et al. (1999)		x	x	
Krause et al. (2013)	x		x	x
Kubta et al. (2017)	x	x	x	
Lange & Imsdahl (2014)	x		x	
Liang & Huang (2002)	x		x	
Markworth et al. (2017)	x		x	
Mesa et al. (2015)	x	x	x	
Mesa et al. (2014)	x	x	x	
Meyer & Lehnerd (1997)	x		x	x
Michaelis & Levandowski (2013)	x	x	x	x
Mikkola (2006)	x		x	
Mortensen & Løkkegaard (2017)	x		x	x
Östgren (1994)	x	x	x	
Parslov & Mortensen (2015)	x		x	
Robertson & Ulrich (1998)	x		x	
Rogers & Bottachi (1997)		x	x	
Sanchez (2013)	x	x	x	
Shuch et al. (2016)	x		x	x
Ulrich & Eppinger (1995)	x		x	

Existing methods, tools and definitions mainly focus on product family design and provide limited support for mapping multiple architectures and explicit relations across domains, which can allow engineers and project managers to understand critical design decisions made across architectures in a large multi-architecture portfolio. In this paper, we want to improve the understanding that these most important characteristics can be encapsulated across an industrial portfolio using the defined BCDRs, establishing a frame for new architecture introduction.

2. Modelling Business-Critical Design Rules

This section describes the modelling principle for BCDRs and uses a manufacturer of white goods as an example. Industrial multi-architecture portfolios generally can be divided into several subcategories, e.g., part features, parts/components, part families, product modules/sub-assemblies, products, product families, product platforms and product portfolios (ElMaraghy et al. 2013) or, as defined by Krause, Eilmus and Jonas (2013): product programs, production programs, product lines, product families and products. When modelling BCDRs, we suggest applying a top-down focus across the portfolio and to put equal focus on the product and manufacturing domains. Thus, we suggest establishing BCDRs at the portfolio, architecture and module levels (Figure 1).

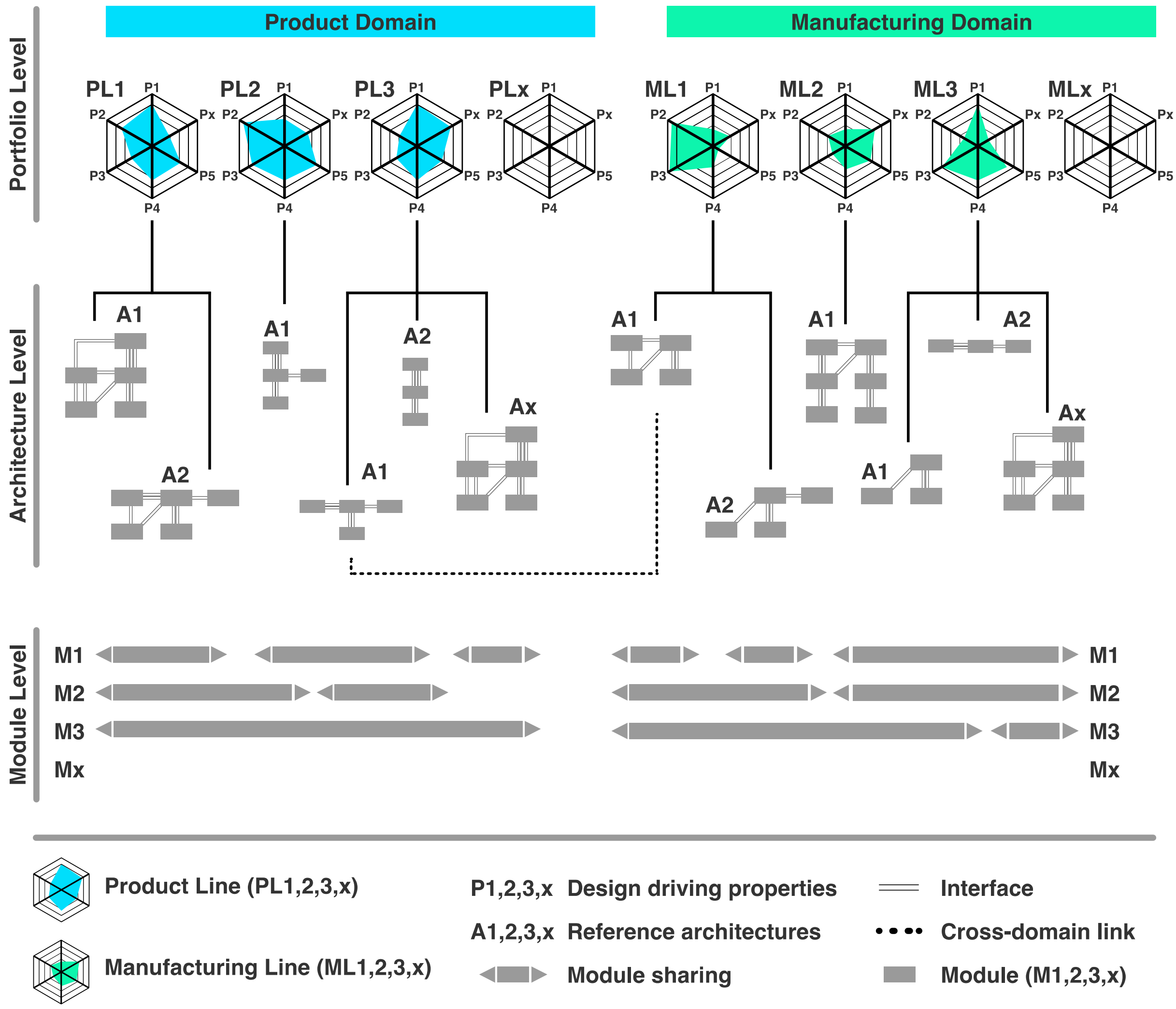

Figure 1. Visualisation of the Portfolio, Architecture and Module Level

2.1. Portfolio level

At the portfolio level, we define several product lines (PL1,PL2,…,PLx) and manufacturing lines (ML1, ML2,…,MLx), which are groups of systems with similar characteristics (Krause, Eilmus and Jonas 2013; Mesa et al. 2015). Using a white-goods manufacturer as an example, different product lines could include washing machines, dishwashers and refrigerators. In the manufacturing domain, examples could be dedicated manufacturing systems (DMS), flexible manufacturing systems (FMS) or reconfigurable manufacturing systems (RMS) (Koren et al. 1999). Building on the concept of design bandwidth, several key properties (P1,P2,…,Px) are defined, spanning the solution space for a line of products or manufacturing systems (Berglun and Claesson 2005; Schuh et al. 2016). The properties can be market-driven, as well as technically and strategically driven, and we argue that identifying these is a somewhat pragmatic exercise. The assumption is that a relatively limited number of decisions dictate most critical design decisions for a line of product or manufacturing systems. These are illustrated using radar plots (Figure 1), indicating the capabilities and limitations of existing product and manufacturing solutions in the portfolio.

2.2. Architecture level

At the architecture level, reference architectures are defined (A1, A2,…,Ax), describing key structural and functional principles for product families within a product line. Several reference architectures can exist within the same line of product or manufacturing systems. Within a line of washing machines, this could be reference architectures for the American or European markets. In the manufacturing domain, it could be reference architecture for automated or manual systems. At the architecture level, BCDRs refer to critical interface decisions in and across reference architectures. The term *reference architecture* describes a somewhat incomplete schematic of the system architecture, only capturing the key elements of the design and highlights in which BCDRs are defined. This resembles the GPPS (Jiao, Zhang and Pokharel 2007) and the Interface Diagram presented by Bruun, Mortensen and Harlou (2014), and it builds on what Parslov and Mortensen (2015) define as A-interfaces, which are considered interfaces with strategic importance, in which a management decision is needed to make design changes. When modelling BCDRs, it is assumed that a limited number of links across domains is critical for new architecture introduction. Building on existing literature, links are considered strategic or constraint-driven. An example could be the outer dimensions of a washing-machine chassis. If the dimensions of a new architecture exceed what is defined in the reference architecture, process equipment cannot handle the component, leading to increased investment, development time and introduction of risk. Defining reference architectures, and the links across these, illustrate where design freedom exists and where top-down and strategic decisions related to interface standardisation and sharing of design principles limit this freedom.

2.3. Module level

At the module level, key modules (M1, M2,..,Mx) are described, and sharing across the portfolio and product and manufacturing lines is visualised. Modules subject to BCDRs are considered off-line modules, which are physical, predefined building blocks shared across reference architectures. Applying off-line modules is in line with what Liang and Huang (2002) define as 'design with modules', in which products are configured out of existing modules or with a design based on a 'construction kit', a collection of predefined elements that define the reference for design (Albers et al. 2015). We argue that it can be essential for efficient new-architecture introduction to define the most critical modules decoupled from other development activities, with the ability to apply these as off-the-shelf solutions. For example, if an organisation allots 24 months from conceptual design to launch for a new product, and process equipment has a lead-time of 18 months, it simply would not be feasible to launch the product in time. Critical modules must be decoupled and developed separately to allow for fast product introduction.

2.4. Visualising BCDRs at portfolio, architecture and module levels: Example

Figure 2 presents an overview of how BCDRs are modelled at the portfolio, architecture and module levels to establish a frame for new-architecture introduction. A company designing and manufacturing washing machines is used as an example. Generally, the product and manufacturing domains are related using a matrix, in which A, B, C, D and x represent segments in which reference architectures exist for both product and manufacturing, and new designs must comply with BCDRs. If a new architecture concept is outside the defined segments in the matrix, it means 'untested' ground and that no direct effects from existing platform efforts should be expected. A segment in the matrix contains a description of the BCDRs at the portfolio, architecture and module levels.

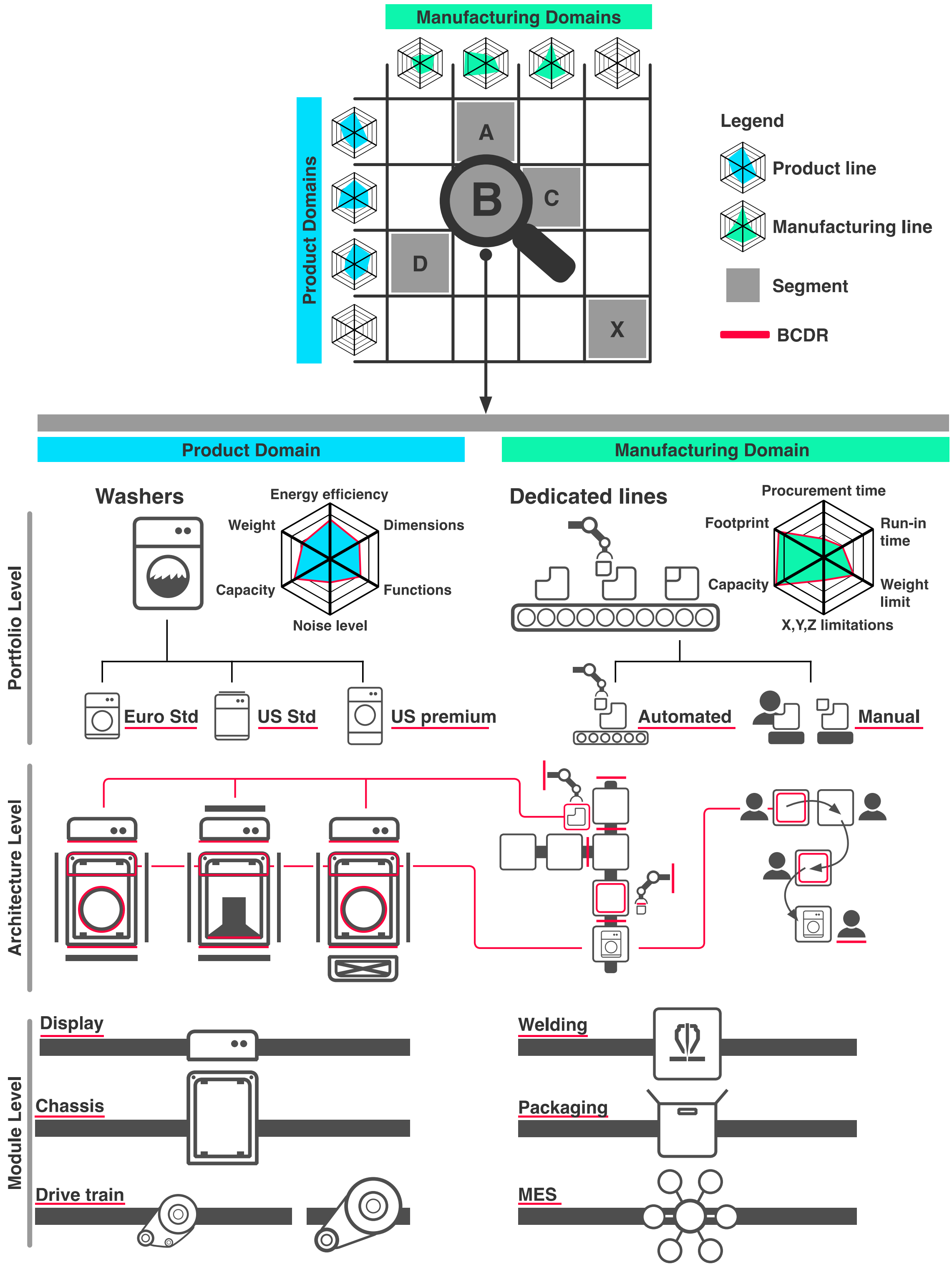

Figure 2. Visualisation of Business-Critical Design Rules

In the example, three reference architectures for product design are defined at the portfolio level: the standard European model, the standard U.S. model and the premium U.S. model. On the manufacturing side, two reference architectures exist: an automated manufacturing system, designed for countries with high labour costs, and a manual and distributed system for assembly in low-cost countries. The main design-driving properties are identified for each domain at the portfolio level (energy efficiency, noise level, capacity, run-in time, etc.). This is illustrated using radar plots. BCDRs denote number of variants and specifications on key design-driving parameters, e.g., a maximum wash capacity and maximum x,y,z limitations of the manufacturing system. At the architecture level, structural and functional decomposition of the systems is described, along with critical interfaces and links across the product and manufacturing domains. For example, standardisation of the interface between the chassis and the display is subject to a BCDR, as this is critical for application of a standard display module and defines a link to the manufacturing domain, enabling late product customisation. Finally, on the module level, three modules on the product and manufacturing sides are defined and considered off-the-shelf building blocks. Considering risk, investments and time-to-market, these modules must be applied when introducing new architectures within the specific segment, e.g., the display, the chassis and the drive train. In the manufacturing domain, the examples cited are the welding cell, packaging cell and manufacturing execution system (MES).

3. Research approach

The suggested modelling principle builds on elements from existing theory within the field of architecture and platform modelling, and has been tested and evaluated in a case study. The study was mainly a prescriptive study (Blessing and Chakrabarti 2009) in which, as researchers, we introduced the suggested modelling principle as support for a modularisation effort at the case company. The primary data-collection methods used were observations, interviews, workshops and internal company documentation, i.e., CAD drawings, bills of material, factory plans, and market data. Visualisation, mainly in the form of visual posters, was used as a communication approach between team members, researchers and managers in which representations of the portfolio could be displayed and used as boundary objects across professional disciplines (Carlile 2002). The generation of BCDRs was a combination of data-driven efforts and input from domain experts. Cost drivers and drivers for time-to-market were identified by going through company data (bills of material, project data, drawings, etc.). Findings were analysed in collaboration with domain experts in a workshop format, including experts from the business, product and manufacturing domains. Outlining a holistic modularisation strategy and establishing BCDR were initiated in August 2015, running over a period of 12 months. During this period, the research team spent more than 100 days on site, engaging with a team of 20 specialists, engineers and managers. The first six months focused on identifying the potential and scope for modularisation at the portfolio level, and the final six months were focused on identifying and formulating BCDRs.

In the product domain, while considering impacts across the portfolio, reference architectures for future products were synthesised, i.e., it was decided which sub-systems should be decoupled to support a strategy of reducing time-to-market. Manufacturing reference architectures were synthesised in a similar way and mapped. However, in the manufacturing domain, optimisation potentials across factories were the main driver for establishing future reference architectures. The strategy was to decouple system dependencies to optimise capacity utilisation through increased flexibility and reuse of equipment. This should reduce investments and development time. The company roadmap played a significant role in the process of identifying BCDRs. The study ended with a consolidated list of critical features to be considered as an obligatory reference for new-architecture introduction.

4. Establishing BCDRs for development of electrical control units

The case company was a large and global OEM designing, manufacturing and delivering approximately 4.5 million electrical control units per year, with an annual turnover of approximately USD 3.5 billion. Throughout the latest product cycles, the company focused extensively on product family design and increasing commonality between variants. However, modularisation efforts had varying effects, as short-term goals often were prioritised at the expense of compliance with overall modularisation strategies. Furthermore, efforts were focused on single product families, with a very limited focus on manufacturing considerations. Product updates, new-product introductions and a focus on time-to-market reduction were the drivers for a new and portfolio-wide perspective on modularisation in the organisation. Historically, major development projects, on average, have a 46-month lead-time from concept phase to product launch, and the new target set by top management was 24 months. This put enormous pressure on the development departments to ensure efficient introduction of new architectures. One way to achieve this was believed to be a strengthening of platform and modularisation efforts. The following sections describe how BCDRs were defined at the portfolio (Figure 3), architecture (Figure 4) and module levels (Figure 5).

4.1. Portfolio level

We have chosen to focus on BCDRs, defined in the core segment of the case company's portfolio, which includes "low-power" electronic control units for heating applications. The products were manufactured for a variety of manufacturing systems, ranging from manual to fully automatic. Approximately 80% of the annual production volume was generated in this segment. Key properties driving product-design decisions were identified combining a baseline analysis of existing product and manufacturing lines with input from domain experts on current and dominating trends. The properties were identified as: (1) power level; (2) need for inputs and outputs, i.e., types and numbers; (3) level of accessibility needed, e.g., the possibility of servicing the product; (4) need for human-machine interfaces (HMI), e.g., LCD display, LEDs, navigation, buttons, etc.; and (5) ambient temperature requirements, defined by operating conditions. In the manufacturing domain design drivers were identified as: (1) test concept, mainly defined by the product power level and test principles; (2) process equipment x,y,z limitations; (3) equipment-weight limitations related to inter-process transportation; (4) automation levels; and (5) annual capacity. A total of six product lines and three manufacturing lines were defined at the portfolio level; they were related through a matrix structure with six segments (A,B,C,D,E and F), in which BCDRs were defined as references for new-architecture introduction (Figure 3).

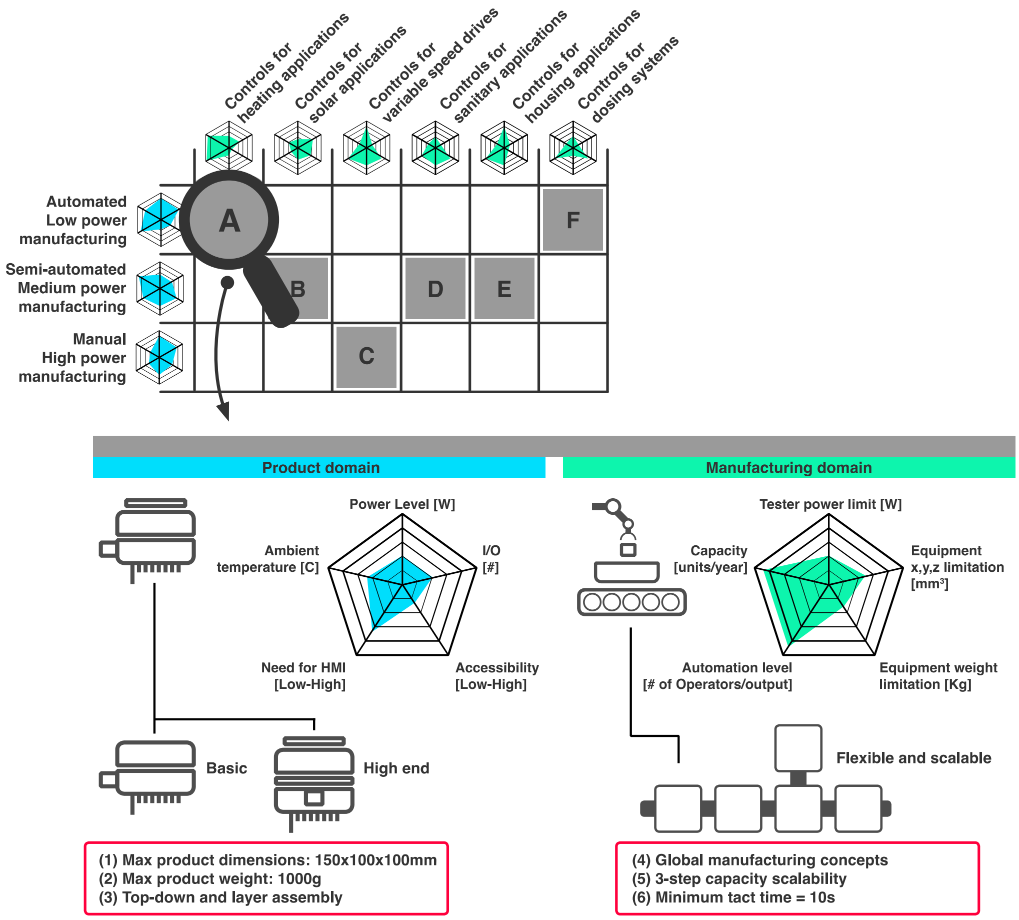

Figure 3. Portfolio level BCDRs in Segment A

In Segment A, constituting the core segment, six critical design rules were defined at the portfolio level (Figure 3): (1) top-down and layer-by-layer assembly of the product, implicating that no side assemblies et al. would be allowed; (2) Manufacturing capacity scalability in three steps. Process equipment should be the same in each step, while the level of automation and the need for automated inter-process transportation and automatic feeding increased; (3) no tact times below 10 seconds; anything below that required radical changes to the reference architecture; (4) clearly defined maximum dimensions and weight limits, allowing for a level of standardisation to be built into grippers, fixtures and pallets (size and support points); (5) single-test concept, as the tester was identified as the main driver for cost and time-to-market aspects; (6) global manufacturing solutions, indicating that no matter where in the world a new manufacturing system was to be built, it would be based on the same reference architecture.

4.2. Architecture level

At the architecture level, reference architectures describing the structural and functional references for designs were defined. In Segment A, this included two product-reference architectures and one manufacturing-reference architecture. At this level, eight BCDRs relating to critical interfaces and links across domains were mapped (figure 4).

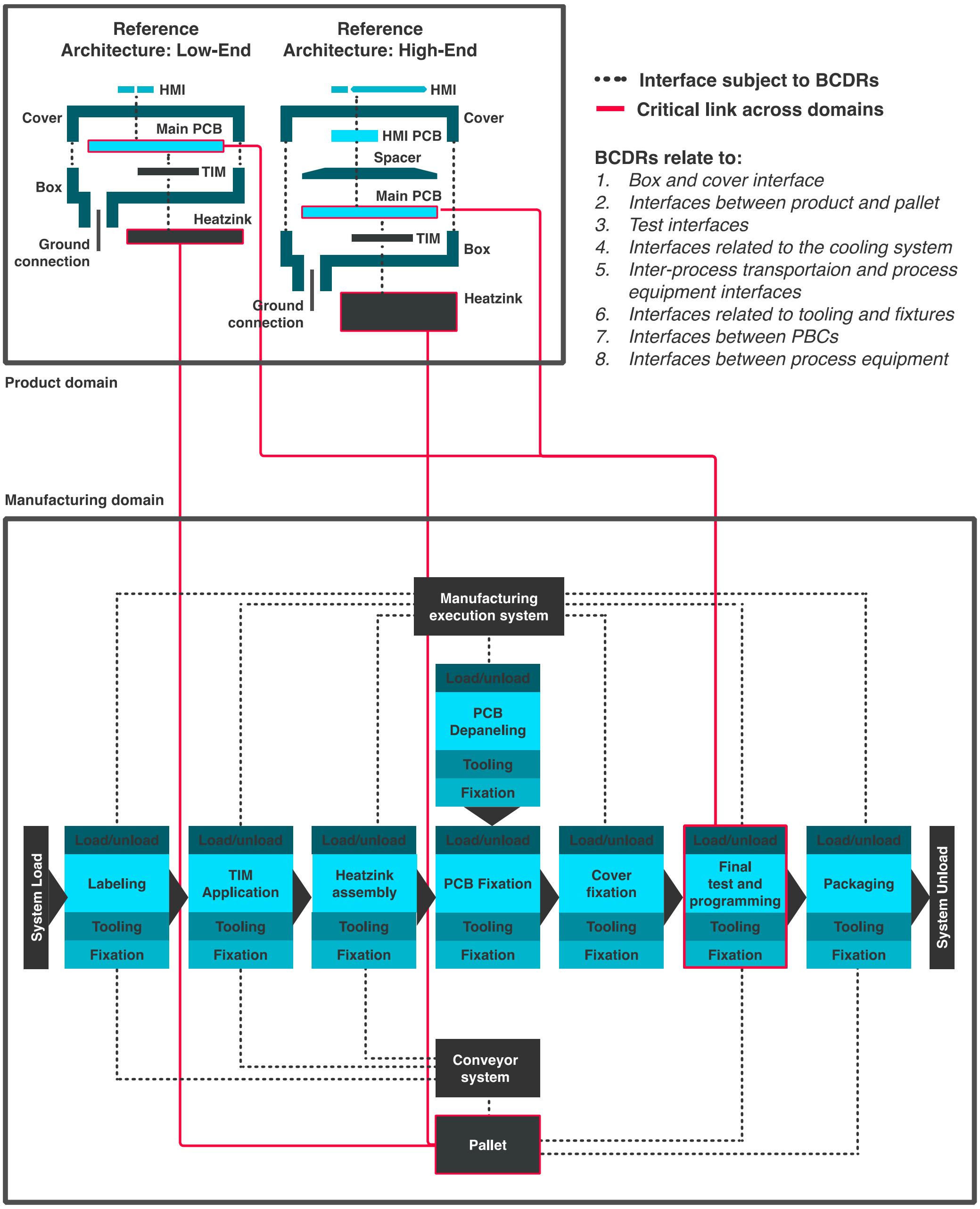

Figure 4. Critical interfaces in and across the product and manufacturing architectures

BCDRs defined at architecture level: (1) The interface between cover and box of the control unit; (2) interfaces from the pallet to the conveyor system and from pallet to the product, e.g., support points and orientation, defining a critical cross-domain link; (3) interfaces and cross-domain links related to the test concept; (4) the thermal interface material in terms of application in the product and manufacturing process; (5) interfaces between the conveyor system, process equipment and system load/unload; (6) interfaces related to tool and fixture changing in the process equipment; (7) interfaces between PCBs; and (8) interface with MES system. Each interface subject to a BCDR was specified and documented to allow compliance evaluation when introducing new architectures.

4.3. Module Level

At this level, a module should be seen as something that can be taken down from the 'shelf' and directly applied in a development project. Critical modules were identified as: (1) test module; (2) cooling module; (3) HMI module; and (4) pallet module (figure 5).

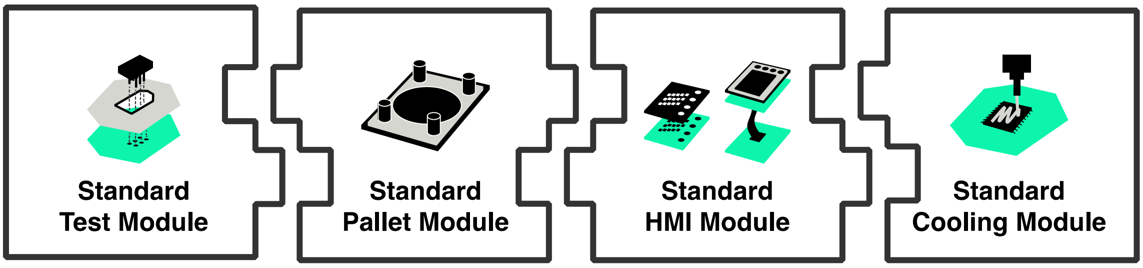

Figure 5. Modules subject to BCDRs

Some modules are relevant for either the product or manufacturing domain; however, some cross over. For example, the test module was defined as a building block in the manufacturing system, but also as a critical driver for the product solution, i.e., by dictating the test interface, distance from entry point to test array and the maximum power level of the product.

4.4. Establishing frame for introduction of new-product and manufacturing architectures

Having defined BCDRs at the portfolio, architecture and module levels helped establish a frame for new-architecture introduction in the organisation, capturing the strategy for sharing platform assets and key design principles. Input from the company roadmap was scrutinised, and implementation was planned based on identified windows of opportunity, i.e., projects were selected to be carriers for development of off-line modules and subject to BCDRs. Figure 6 summarises how the frame for design was established in the core segment of the company's portfolio.

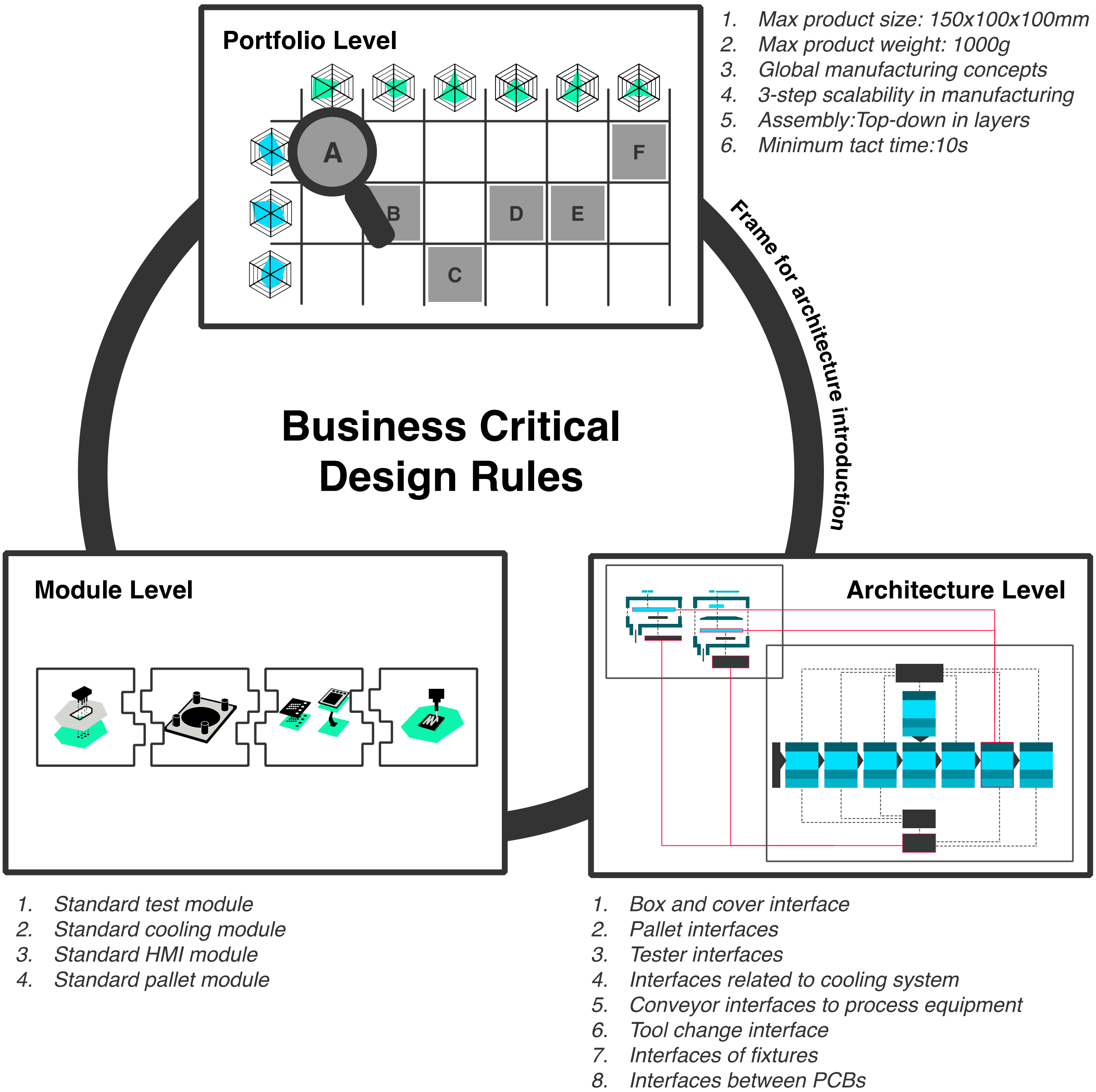

Figure 6. Overview of BCDRs identified in the case study

BCDRs were defined as guidelines for how new products and manufacturing systems should be designed to ensure alignment with the overall strategy for time-to-market reductions. The production manager and key stakeholders said defining and agreeing on the basic rules for design would allow for an average of two months to be cut from the concept phase for all new product introductions. Encapsulating structural and functional design rules, critical for the execution of modularisation as a strategy, helped create this frame, enabling designers to become familiar with the playing field, thereby improving capabilities for introducing new innovations. Furthermore, the approach revealed a potential for reducing investments in new manufacturing equipment. Traditionally, dedicated lines were built when introducing a new product architecture. However, knowing the capabilities of the existing manufacturing lines, support was created for new architectures to be a run-in on existing equipment, potentially reducing investments in manufacturing. Integrating newly planned manufacturing lines, existing lines and roadmap considerations highlighted a potential for a 35% reduction in investment through optimisation of equipment utilisation.

5. Discussion

Designing product and manufacturing systems with an embedded level of modularisation can be challenging, and governance is needed to realise the benefits of interface standardisation and application of standard platform assets. Effects are realised over time, thus, stability related to critical design decisions is important. Modelling BCDRs provides a way to communicate important design knowledge and a way to guide designs from a top-down perspective, with an emphasis on a company’s strategic aims for modularisation.

As indicated in the review of literature, description and development of modular architectures and platforms are relatively well-supported. However, when introducing new architectures in a multi-architecture portfolio, support is limited for communicating strategic-design decisions on modularisation, platforms, and relations between product and manufacturing architectures. The strength of modelling BCDRs is, on a managerial level, the ability to clearly communicate strategic directions on modularisation to project teams and engineers. This provides a frame for development by clearly illustrating existing solutions, their capabilities and obligatory design rules to follow when introducing new-product or manufacturing architectures in the portfolio.

Based on the analysis of related literature (Table 2), Table 3 provides an overview of the identified methods and tools supporting a level of cross-portfolio thinking in relation to modularisations. The table illustrates how the suggested framework for mapping BCDRs contributes to this knowledge base.

Table 3. Relevant papers applying a cross-portfolio perspective to modularisation

Support for:	Module sharing across product architecutes	Describing product architecture characteristics	Module sharing across manufacturing architecture	Describing manufacturing architecture characteristics	Describing critical links across product and manufacturing architectures	Using existing design knowledge as reference for product introductions	Portfolio level considerations on number of architectures/ platforms
Cleasson (2006) - CC	x	x	x	x	x		
Meyer & Lehnerd (1997) - PPP	x	x	x	(x)			(x)
Karuse et al. (2013) - PKT	x	x	(x)	(x)	(x)		x
Michaelis & Levandowski (2013) - SBCE/CC	x	(x)	x	(x)	x	x	
Mortensen & Løkkegaard (2017) - ADP	(x)	(x)			(x)		(x)
Borjesson & Hõlltä-Otto (2014) DSM/MFD	(x)	x	(x)				
Fixson (2005) - PAF		x		(x)	(x)	x	
Berglund & Cleasson (2005) - DB/CC	(x)	(x)				x	
Baldwin & Clark (2000) - DR	x	x				(x)	
Lange & Imsdahl (2014) - MFD	x	x		(x)			
Husan & Hansen (2007) - PPM	(x)	x					(x)
Shuch et al. (2016) - MSCA	(x)						(x)
Modelling BCDRs	(x)	(x)	(x)	(x)	x	x	x

x - Modelling principle, method, definion
(x) - Addressed
Main contribution

CC - Configrable component framework
PPP - Power of product platforms
PKT - PKT Approach
SBCE - Set-based concurrent engineering
ADP - Architecture Design Principles
DSM - Design Structure Matrix

MFD - Module Function Deployment
PAF - Product Architecture Framework
DB - Design bandwidth
DR - Design Rules
PPM - Platform Portfolio Matrix
MSCA - Multidimensional scaling and cluster analysis

The suggested framework stands out as it supports capturing critical links across product and manufacturing architectures, supports using this design knowledge to frame new architecture introduction in multi-architecture portfolios and, from a top-down perspective, allows industrial organisations to consider the number of existing architectures and platforms across a large portfolio. Mapping BCDRs allows, in an operational way, to communicate this important design knowledge. The benefit is that design decisions related to modularisation efforts and application of platform assets can be effectively governed across an ever-evolving multi-architecture portfolio, to increase the chances for harvesting related effects of standardisation.

In the manufacturing domain, defining BCDRs generally can affect several aspects of performance, e.g., investments, utilisation, scaling, delivery performance, quality, etc. This is considered highly dependent on the specific company context. As seen in the case study, establishing a frame for new-architecture introduction, based on several defined BCDRs, has the potential to optimise manufacturing-capacity utilisation by improving the ability to run-in new architectures on existing equipment. This was the result of improved communication of manufacturing capabilities across the portfolio and deciding on several critical design principles.

Managing relationships across product and manufacturing architectures generally is recognised as important for efficient new-product launches and time-to-market aspects (Carrillo and Franza 2006; ElMaraghy and AlGeddawy 2014; Gudlaugsson et al. 2016). At the portfolio level, segmentation based on the matrix (Figure 2) provides an overview of existing product and manufacturing lines, their main design-driving characteristics and how the domain relates. This allows designers to assess which product or manufacturing line a new concept is compliant with and which BCDRs to follow. At the architecture level, links across domains are related to critical interfaces. As demonstrated in the case study, the test interface was an important driver for investments and time-to-market, and thereby elevated to a BCDR. Practically speaking, this meant that new designs all should allow top-down testing through a standardised opening in the product, have a maximum distance to the PCB of 8mm and have standardised test software preloaded on the PCB prior to testing. Changing any of these parameters would require significant investments in manufacturing and influence time-to-market negatively. These factors make the test interface an excellent example of what, at the architecture level, should be defined as a BCDR.

Validation of the suggested modelling principle for BCDRs has been limited to a single case study. The case company was a large industrial OEM with a portfolio counting multiple product families and related manufacturing solutions. The desire to reduce time-to-market was the main driver for modelling BCDRs in the case company. However, at the current state, it is not possible to quantify a direct effect. We can support the evaluation through qualitative statements from the case company, in which an agreement was established on the validity of the approach. Top management's increasing involvement throughout the process was seen as an indicator of the approach, providing new value related to executing modularisation as a strategy in the organisation. Toward the end, the head of development elevated the defined BCDRs as a reference for all new development projects in the organisation. Future research activities will be focused on applying the concept in different contexts to further validate and generalise the modelling principle. This includes application in smaller organisations. Furthermore, with the possibility to assess effects over time, future research efforts will be focused on quantifying the direct effects of modelling BCDRs.

Top management commitment has been stated as a critical factor for succeeding in modularization efforts (Sanchez, 2013). We believe that modelling BCDRs provides an important contribution in relation to existing challenges. In a relatively simple and pragmatic way, it forces organisations to formulate their strategies by directly linking them to critical design decisions across the portfolio. An area for future research opportunities includes developing quantitative performance indicators to support the use of BCDRs as a guiding factor for new-architecture introduction. Meaning that, for example, in a stage-gate process, compliance with BCDRs could potentially be evaluated as a prerequisite for gate passages. However, a framework is needed for this type of evaluation. Finally, the suggested modelling principle has been limited to a product and manufacturing focus. It could be interesting to expand the scope and include an explicit focus on supply chain considerations (Sawik, 2017) and market domains when modelling BCDRs.

6. Conclusions

The main contribution of this work is the introduction of a modelling principle for BCDRs at the portfolio, architecture and module levels. It has been possible to establish BCDRs for a large industrial OEM to support a corporate modularisation strategy focused on time-to-market reductions. Modelling BCDRs has provided a frame for new-product introduction and has served as a starting point for defining a modularisation strategy at the portfolio level.

We conclude that it is beneficial to govern new architecture introduction based on several design rules related to product and manufacturing design. Focusing only on a limited number of critical decisions allows the task to be manageable and communicated within a large organisation. Key stakeholders at the case company commented that agreeing on key elements in and across domains (e.g., pallet size, IT system interfaces and line-reference architectures) could cut, on average, two months of development time at the concept phase. Adding the effect of parallel development possibilities and application of standardised off-line modules, the approach is believed to be able to support organisations in improving time-to-market for new-product introductions.

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