Design Science

Set-based design: a review and new directions

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Abstract

Set-based design (SBD), sometimes referred to as set-based concurrent engineering (SBCE), has emerged as an important component of lean product development (LPD) with all researchers describing it as a core enabler of LPD. Research has explored the principles underlying LPD and SBCE, but methodologies for the practical implementation need to be better understood. A review of SBD is performed in this article in order to discover and analyse the key aspects to consider when developing a model and methodology to transition to SBCE. The publications are classified according to a new framework, which allows us to map the topology of the relevant SBD literature from two perspectives: the research paradigms and the coverage of the generic creative design process (Formulation–Synthesis–Analysis–Evaluation–Documentation–Reformulation). It is found that SBD has a relatively low theoretical development, but there is a steady increase in the diversity of contributions. The literature abounds with methods, guidelines and tools to implement SBCE, but they rarely rely on a model that is in the continuum of a design process model, product model or knowledge-based model with the aim of federating the three Ps (People–Product–Process) towards SBCE and LPD in traditional industrial contexts.

Key words: design research, product development, lean product development, concurrent engineering, set-based concurrent engineering, set-based design

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1. Introduction

Lean thinking applied to product development, often called lean product development (LPD), has received positive and steadily increasing attention with the objective of revolutionizing product development (León & Farris 2011). Originally witnessed at Toyota and labelled the Toyota Product Development System (Morgan & Liker 2006), LPD has evolved, from adapting the more mature theories and principles of lean manufacturing to the realm of engineering, to then become considered on its own. The theory includes inner principles and lean thinking concepts applied to product development such as waste (Oehmen & Rebentisch 2010), value/knowledge focus (Browning 2000; Ward & Sobek 2014) and flow (Browning 2000; Oppenheim 2004; Reinertsen 2007; Beauregard, Bhuiyan & Thomson 2014). Lean product development was described with its enablers, which has allowed for the construction of several models and frameworks suitable for lean product and process development practical implementation, theory-building and continuous research

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(Kennedy 2003; Morgan & Liker 2006; Hoppmann *et al.* 2011; León & Farris 2011; Khan *et al.* 2013; Ward & Sobek 2014). For instance, set-based design (SBD) (also set-based engineering or set-based concurrent engineering (SBCE)) has emerged as a key enabler of LPD. Indeed, SBD is a field of active research, with the purpose of either leveraging its principles based on the claimed efficiency of the design methodology (e.g., Raudberget (2015)) or integrating it into a framework for implementing lean product and process development as a whole (e.g., Khan (2012)). Nevertheless, studies on LPD in the industry show that its maturity of implementation in industry is low, no more than an introductory level and it has not been possible to find a company that coherently combines the LPD enablers into a whole to improve the company product development process in a lean way (McManus, Haggerty & Murman 2005; Rebentisch 2008; Beauregard *et al.* 2014; Al-Ashaab *et al.* 2016). With a focus placed on SBD, which is the design strategy in LPD, the objective of this current review is to find answers to the following questions:

(i) *What is the state of the art of SBD literature?*
(ii) *What are the most important contributions to the SBD focusing on the development of a model and methodology?*
(iii) *What are the key aspects to consider when developing such a model and methodology?*

The article consists of a study of SBCE research from 1987, the year in which publications on the Japanese product development practices began to appear, to 2017, which represents the end of the data collection. The review is drawn from an evidence-based systematic review procedure (Nissen 1996; NHS 2001; Tranfield, Denyer & Smart 2003), which is applied herein by using methods similar to (León & Farris 2011) and (Baines *et al.* 2006) in their reviews of LPD body of knowledge.

The remainder of the article is organized as follows. First, SBD theory and principles are discussed. Then the analytical framework and strategy used to review the literature are presented. The results of the review are discussed in Section 4 by means of quantitative analysis. Using the proposed framework, the selected contributions are then summarized and correlated in Section 5. New paths of research are discussed before the article is concluded in Section 6.

2. Set-based design

According to Clark & Fujimoto (1991), the earliest decisions in product development have the largest impact on the overall quality of the product (effectiveness) and the overall cost of the project (efficiency). Many approaches to engineering design are focused on reducing cycle time following the famous motto 'do it right the first time'. In terms of design strategy, this has often been translated into a need to propose the right solution as fast as possible. As observed by Sobek & Ward (1996), when dealing with the development of complex products, many companies force the engineering teams to propose a feasible concept quickly so that it can then be optimized through numerous iteration loops. This pattern is understood as point-based because it focuses on one solution at a time and progressively refines it until all the stakeholders are satisfied with the outcomes. Figure 1 illustrates this view. A point in the design

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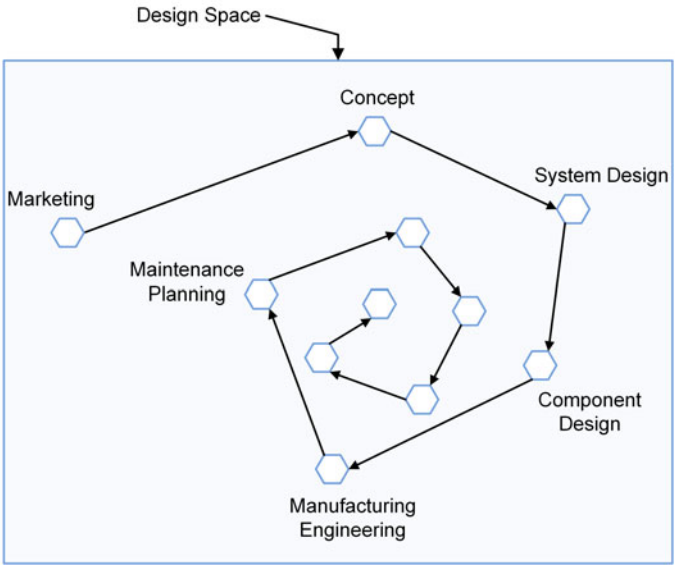

Figure 1. A point-based approach to the design of a complex product. Adapted from Ward *et al.* (1995).

space represents a single solution from a given discipline while interacting with the others, whereas in Figure 2 the set of solutions is reflected by an area in the design space.

Another design strategy, the set-based approach, has been the subject of a number of publications over the past 20 years. It is one of the pillars of lean thinking applied to product development, again observed particularly in the automotive industry through companies such as Toyota, Honda, or Denso. Here, engineers may reason and communicate about an acceptable range of parametric values instead of the single best value at a time. Set-based design allows windows of possibilities to align gradually and therefore the best of all worlds to be projected. It is rather a convergence process than an evolution (Sobek & Ward 1996). Participants bring sets of possibilities to the table and juxtapose them to find an intersection of feasibility rather than successively criticizing and modifying a single option (Liker *et al.* 1996). Figure 2 illustrates the approach.

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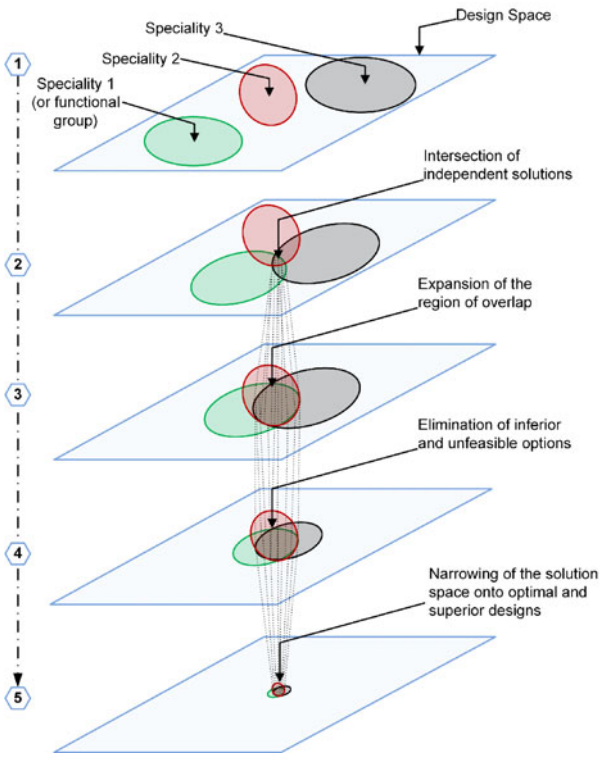

Figure 2. A set-based approach to the design of a complex product. Adapted from Bernstein (1998).

Set-based design space awareness and thorough exploration extend the classical vision by enabling a broad discovery of the design space. This avoids narrowing too quickly on discrete areas of the space and thereby losing the potential for innovation and discovery. However, the additional costs incurred by supporting multiple alternatives long into the development process could be detrimental. To help companies better strategize their set-based exploration efforts, Ward & Sobek (2014) propose to divide their development projects into four categories: tailoring; strategic breakthrough; limited innovation & reintegration; research. The approach is combined with probabilistic calculations to determine the optimal number of alternatives/prototypes to pursue given the probability of failure of a system or subsystem design (product of the probabilities for the individual concepts). The expected cost of failure is also considered (cost to the whole system). The calculation essentially focuses on reducing the risk of a development project failure by indicating areas that require broader evaluations (cheap, early in the development process). This usually yields a higher probability of success compared to the probability of failure that results from unknowingly pushing a potentially weak option far in the product development process (PDP). This is confirmed by Camburn *et al.* (2017) and Camburn *et al.* (2015) through empirical research. By aggressively eliminating weak options early in the PDP and thereby confidently concentrating on robust areas that can guarantee flexibility, discovery and innovation, set-based approaches to

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design make strategic prototype planning/execution a key factor of success in development programmes.

Sobek, Ward & Liker (1999) described the three principles of SBCE, which according to Ghosh & Seering (2014) have remained the same as that used for SBCE discussions and implementations across the research and industrial applications.

(1) Map the design space:
  (i) Define feasible regions
  (ii) Explore trade-offs by designing multiple alternatives
  (iii) Communicate sets of possibilities
(2) Integrate by intersection:
  (i) Look for intersections of feasible sets
  (ii) Impose minimum constraint
  (iii) Seek conceptual robustness
(3) Establish feasibility before commitment:
  (i) Narrow sets gradually while increasing detail
  (ii) Stay within sets once committed
  (iii) Control by managing uncertainty at process gates

Several methods like the morphological chart (Cross 1989), the method of controlled convergence (Pugh 1991), the Design–Build–Test cycle (Wheelwright & Clark 1992), the fuzzy inference-based concept convergence process (Augustine *et al.* 2010) and the configurable component (CC) based platform (i.e., product platform strategy) (Wahl & Johannesson 2010) share similarities with SBCE (design strategy), in the sense that they all use the exploration of multiple alternatives to converge within the design space or the design *bandwidth*.[1] The main specificity of SBCE is twofold: (1) in SBCE, speciality groups can independently analyse their design options (sets of design alternatives) and then intersect at integration events, which then eliminates the iterative path that is problematic in the point-based approach (Sobek & Ward 1996; Bernstein 1998); (2) SBCE delays decisions to learn by experimentation (extensive prototyping) and additionally front-load the design/development (reuse/recycling of existing knowledge) before narrowing the design space by elimination of unfeasible designs (Morgan & Liker 2006; Ward & Sobek 2014). Prototyping, learning and the reuse of existing well-structured information and knowledge are therefore important aspects of SBCE.

3. Review strategy and analytical framework

The methodology followed to perform the review is an evidence-based procedure described by Tranfield *et al.* (2003). SBD theoretical grounds were presented in the previous section, which led to the extraction of important aspects of the approach such as the exploration of a design space, the extensive use of prototypes and the very specific concurrent engineering practices that

[1] The concept of the design *bandwidth* in product platform design is described in Berglund & Claesson (2005).

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involve the ability to communicate about sets. 'Design space', 'prototyping' and 'concurrent engineering' are selected keywords for the procedural search following this preliminary synthesis. From a practical product development standpoint, handling multiple design alternatives during the development process usually calls for configurability of the product (or the platform) as a prerequisite (Van Veen 1991; Hegge 1995; Wortmann & Erens 1995; Erens 1996; Sabin & Weigel 1998; Männistö *et al.* 2001; Claesson 2006; Claesson & Johannesson 2006). This aspect is considered herein as a key element from a practical product development implementation perspective. As a result, the combination of keywords selected to query the research databases goes as follows:

(i) Keyword 1 (**KW1**): set-based + concurrent engineering
(ii) Keyword 2 (**KW2**): set-based + prototyp*
(iii) Keyword 3 (**KW2**): SBCE
(iv) Keyword 4 (**KW3**): set-based + design space
(v) Keyword 5 (**KW4**): set-based + configur*

As this work pertains to engineering sciences and the related cognitive and social sciences, the research databases selected for the data extraction are *Compendex* and *Inspec* (EBSCO) for engineering research publications and *Web of Science* (Thomson Reuters) to cover the broader landscape of sciences related to design as a cognitive and social science (for the dynamics of social organization). Databases like Proquest (ABI Inform), which contain dissertations and other institutional publications, are not included to focus on peer-reviewed work. This is done assuming that backtracking through the peer-reviewed work will allow us to consider the related comprehensive institutional publications. Similarly, backtracking allows us to explore influences and also new areas of the subject, which are not otherwise nominally related to the topic as queried. This mitigates the limitation of solely relying on keyword searches.

Table 1 displays the result of the data extraction. The extraction resulted in a total of **1733** publications. After duplicate records were removed, the remaining **921** records were collated to form the pool of publications to distribute by the categories 0 to 5 described below.

Table 1. Data extraction

Keyword combination	Hits			Total
	Engineering Village (Compendex) (1987–2017)	EBSCO (Inspec) (1987–2017)	Web of Science (Thomson Reuters) (1989–2017)	
Set-based + concurrent engineering	142	54	68	264
Set-Based + Prototyp*	109	86	113	308
SBCE	48	27	110	185
Set-based + Design Space	181	124	169	474
Set-based + Configur*	183	140	179	502
		Grand Total		**1733**
		Duplicates removed – Collated, Total		**921**

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The research area and the content of the 921 publications were examined to perform a preliminary assessment with the purpose of assigning a category to the publication as inspired by León & Farris (2011) and Nissen (1996). The categories that emerged from the preliminary assessment are listed below by adhering to the distinctions (Gericke, Eckert & Stacey 2017) that must be made among a method, process, tool, guideline and a methodology:

(i) Category 0 (767): The publication is not relevant to the review because of the content and the classification of the research area, e.g., content related to set theory and pure level set methods, classifications such as graph theory, set theory, signal processing, mathematics, imaging science and photographic technology.
(ii) Category 1 (29): The publication develops on methods that facilitate SBCE, e.g., fuzzy sets, interval sets and computational design synthesis.
(iii) Category 2 (46): The publication explores the combination of SBCE principles with a complementary design method in order to accelerate or improve the design/development process, e.g., multidisciplinary design optimization combined with SBCE principles.
(iv) Category 3 (19): The publication emphasizes lean concepts with more or less considerations for SBCE.
(v) Category 4 (36): The publication reports on the practical application of SBCE principles and tools.
(vi) Category 5 (24): The publication emphasizes the development of SBCE theories, models and methodologies for SBCE practical implementation. This category consists of the 24 publications that are considered the most important contributions with regard to the second and third objectives of the review. The category contains the contributions to classify according to the new framework.

Indeed, a new classification framework is proposed in this review with the goal of mapping the topology of the most relevant SBD literature from two perspectives. The first is the coverage of the engineering design process when it comes to proposing/developing models and methodologies for the practical implementation of SBD, i.e., SBCE. The second is the research paradigms/methods chosen by the SBD research.

SBD belongs to the lean philosophy and as such can be assessed through the fundamental continuous improvement cycle, i.e., PDSA, *Plan–Do–Study–Act* (Deming 2000), as well as the fundamental value creation cycle, i.e., LAMDA, *Look–Ask–Model–Discuss–Act* (Ward & Sobek 2014). An additional layer may also involve mapping each step of these cycles to the generic creative design process (Formulation–Synthesis–Analysis–Evaluation–Documentation–Reformulation) (Howard, Culley & Dekoninck 2008) as perceived from the SBCE perspective, i.e., *Explore* (formulate, map the design space); *Generate* (synthesize/analyse alternative designs); *Learn* (evaluate, document, communicate); *Refine* (overlap design options, eliminate weak options, reformulate). The practical implementation cycle steps aligned with the SBCE design process steps altogether result in four dimensions/areas for analysing the literature. These dimensions/areas can be decomposed into segments representing the granular concepts, approaches, techniques and catalysts for which the use and implementation in the literature might be explored with the purpose

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of proposing/developing models and methodologies intended to support the transition to SBCE. The proposed classification framework is shown in Figure 3 in the form of a continuous improvement cycle. Each segment is described further in Sections 4 and 5 by correlating it to the publications.

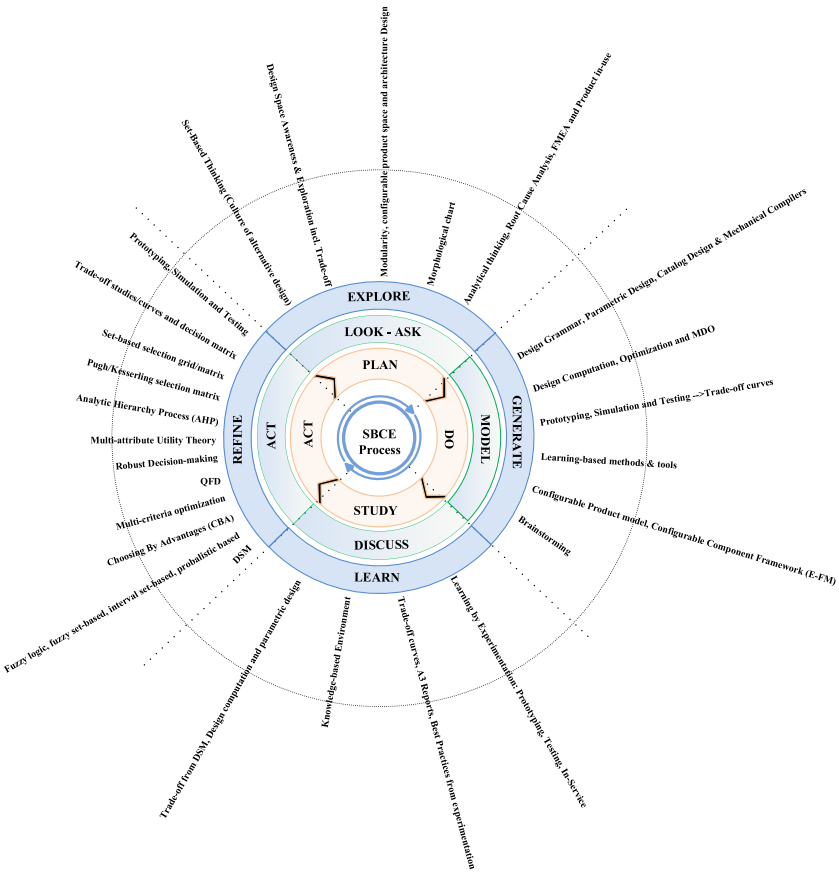

Figure 3. Set-based design process classification framework.

Another way to categorize the literature is to identify the research paradigm and the methods used in the research publications. The aim is to objectively perceive the purpose of the research, the type of enquiry, inference and construction used by the researchers, as well as the typical outputs and theory-building versus practical implications that can be expected from the research (Hoepfl 1997; Hart 1998). The research methods in particular reveal the type of enquiry and, therefore, the type of answers a research work can provide. From an epistemological standpoint, researchers fundamentally take stances that can be explicit or rather implicit. Figure 4 shows the proposed SBCE literature research paradigm classification framework.

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Figure 4. Research paradigm classification framework.

4. Progression, maturity and impact of SBCE research

The majority of publications (i.e., 46 out of 154) (30%) consists of research papers that combine SBCE principles with complementary design methods to improve the design/development process. The publications in this category 2 frequently focus on the design synthesis and selection process by portraying how the other method could adequately fit the SBCE concept generation, exploration and selection process. This denotes a growing interest in SBCE from diverse field areas. It also suggests a pervasive influence of SBCE, especially on methods and techniques for early stages of the development process. Examples, to name a few, include the combination of SBCE principles and techniques with the following:

(i) Multi-objective problem/multidisciplinary optimization (Moshaiov & Avigad 2007; Avigad & Moshaiov 2009, 2010; Hannapel, Vlahopoulos & Singer 2012; Hannapel & Vlahopoulos 2014; Sasaki & Ishikawa 2015), Constraint Satisfaction Problem (CSP) (Ishikawa & Nahm 2005; Nahm & Ishikawa 2005; Nahm, Ishikawa & Yang 2007; Qureshi *et al.* 2010; Canbaz, Yannou & Yvars 2011; Inoue *et al.* 2012, 2013*a*; Wang *et al.* 2013; Yannou *et al.* 2013; Kizer & Mavris 2014)

(ii) Model-based systems engineering (ElMaraghy & Jack 1993; Toche *et al.* 2012; Cho, Lee & Bae 2014; Becker & Wits 2015; Essamlali, Sekhari & Bouras 2016)

(iii) Game theory (Pourabdollahian, Taisch & Kerga 2012; Kerga *et al.* 2014*a*,*b*)

(iv) Bayesian networks (Shahan & Seepersad 2009, 2012; Matthews *et al.* 2014)

Figure 5 displays the distribution of the 154 relevant publications by categories.

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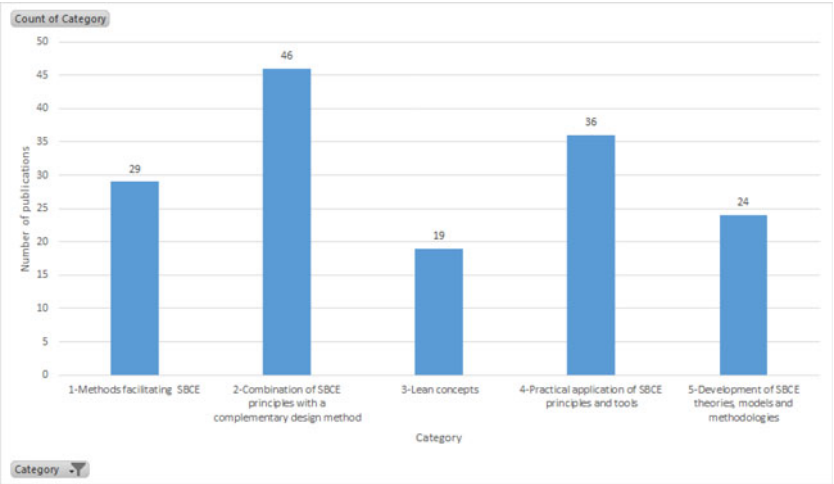

Figure 5. Distribution of category 1–5 publications.

Category 1 is very similar to category 2 with the only difference that category 1 focuses on the method itself (e.g., fuzzy set-based approach, interval set propagation, method of imprecision (MoI), etc.) and the means by which it can facilitate SBCE (e.g., Otto & Antonsson (1995), Ward (1989), Finch & Ward (1997)). The authors in category 1 typically display complementary publications in category 2 where the novel approach that combines SBCE with the expert method is forwarded, but the two categories are not always easy to separate on this sole basis. Category 1 examples include these works (Hernandez-Luna & Wood 1994; Antonsson & Otto 1995; Ong & Nee 1998; Ong, Sun & Nee 2003; Shan & Wang 2003; Wang & Shan 2004; Panchal *et al.* 2007; Zhai, Khoo & Zhong 2009; Hernandez-Luna, Moreno-Grandas & Wood 2010; McKenney *et al.* 2011*a*; Canbaz, Yannou & Yvars 2014; Qureshi *et al.* 2014; Kawakami *et al.* 2016). One can therefore argue that categories 1 and 2 could merge into one single category about discrete methods that facilitate SBCE.

Category 4 comes in the second position with 36 of the 154 publications (23%). The category consists of publications on the practical application of SBCE principles and tools. Examples include these works (Giachetti 1997; Ford & Sobek 2005; Parrish *et al.* 2008*a*; Ishikawa & Inoue 2009; Raudberget & Sunnersjö 2010; Takai 2010; Raudberget 2010*a*,*b*; McKenney, Kemink & Singer 2011*b*; Maksimovic *et al.* 2012; Rocha, Affonso & De Oliveira 2012; Kerga, Khan & Arias 2012*a*; Kerga, Taisch & Terzi 2012*b*; Neeley *et al.* 2013; Rocha, Affonso & De Oliveira 2013; Inoue *et al.* 2013*b*; Kennedy, Sobek and Kennedy 2014; McKenney & Singer 2014; Araci, Al-Ashaab & Maksimovic 2015; Landahl, Raudberget & Johannesson 2015; Bertoni *et al.* 2016; de Souza & Borsato 2016; Heikkinen *et al.* 2016; Landahl *et al.* 2016; Maulana *et al.* 2016; Elhariri Essamlali, Sekhari & Bouras 2017). These publications are distinguished from the ones in category 5 as they do not attempt to develop actual SBCE theories, models and methodologies. The publications in category 5 consist of the 24 most important publications with regard to the main objectives of the review. They will be examined in detail in Section 5 by using the

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proposed analytical framework. The following subsections discuss the state of the art of SBD by means of quantitative analysis.

4.1. Progression of SBCE research

Bibliometrics are used in this section in order to obtain insights into the topology, progression, maturity and relevance of SBCE research. The age profiles of the publications from all categories (1 to 5) are shown in Figure 6.

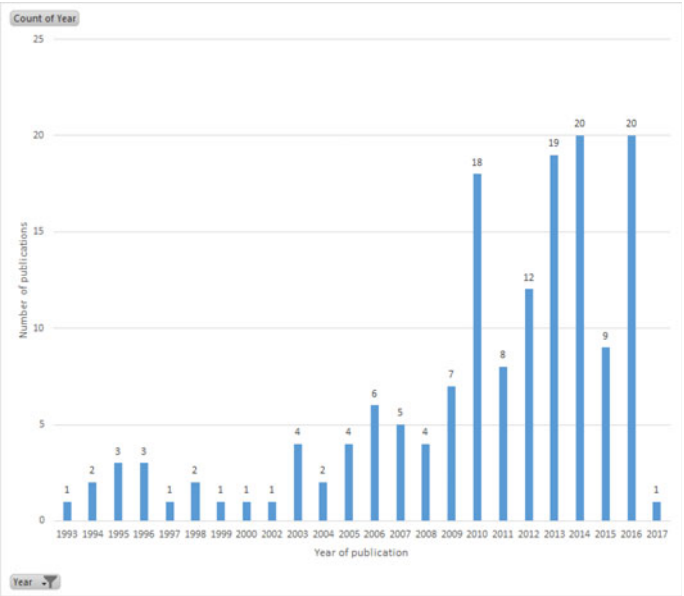

Figure 6. Age profile of the publications (category 1–5).

The profile discloses a fluctuating growth of SBCE publications from 1993 onward, with a proliferation starting around 2010. There are two potential reasons for the relative absence of SBCE related publications between 1987 and 1993. First, set-based concurrent engineering, as it refers to Toyota's practice, was coined by Ward *et al.* (1994) in their landmark paper presented at the proceedings of the 1994 ASME Design Technical Conferences in Minneapolis, USA. Second, even though early 90s' research on engineering design calculations clearly involved set-based reasoning (see fuzzy parameters, labelled interval calculus and other methods like the MoI and constraint satisfaction) (Antonsson & Wood (1989), ElMaraghy & Jack (1993), Hernandez-Luna & Wood (1994), Hyvönen (1992), Tommelein (1989), Ward (1989), Wood, Otto & Antonsson (1992)), they did not entail the holistic SBCE philosophy and principles, institutional knowledge capture and reuse advocated enabling a superior product development (PD) process (see previous descriptions of LPD and SBCE). Moreover, these early research efforts involving set-based methods were not always nominally identified as such, which is the reason why some may not be retrieved by keyword search. The complementary publications are discussed in this article as discovered by

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backtracking through the references. The proliferation of SBCE research in the 21st century, especially in the past 10 years, suggests a growing interest in the field, which might be generated by a context of compelling socioeconomic factors in the aftermath of the global financial crisis (2007–2008). These factors have demanded responsive, flexible, agile and LPD processes for companies to stay competitive in rapidly changing markets. There might be other reasons for the proliferation, which could not be established on the sole basis of evidence from this review.

4.2. Maturity and impact of SBCE research

Following the restriction to peer-reviewed publications, the pool of 154 relevant publications is split between journal articles (40%) and proceeding papers (60%). The authors concur herein with León & Farris (2011) that the relative number of publications in scientific journals remains an objective indicator of fundamental and theoretical development into a field. Consequently, it can be argued that the relatively small number of journal publications on SBCE indicates a low theoretical development of SBCE. Nevertheless, a wide variety of journals (36) have published SBCE related papers. This variety is the result of SBCE being explored from diverse perspectives, i.e., knowledge domains.

The age profile chart shows evidence of a growing popularity and interest in SBCE, but it provides less information on the maturity and importance of the field of research. Assessment variables that can support such analysis include the ratio between peer-reviewed and non-peer-reviewed publications, the count of publications in journals and the ranking of the journal by indexes such as the Total Cites, Impact Factor (Journal Citation Reports® published by Thomson Reuters) and the Eigenfactor® score(eigenfactor.org). Table 2 lists the Total Cites, Impact factor and Eigenfactor score of the journals that published the SBCE content extracted for the review. These criteria were not used to include or exclude a publication. They are discussed as a means to comparatively assess the relevance, importance and visibility of SBCE research based on the metric.

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Table 2. Total Cites, Impact Factor and Eigenfactor Score

Journal	Tally	Total Cites	Impact Factor	Eigenfactor
Advanced Engineering Informatics	2	1237	2.000	0.002760
Business Strategy Review	1	n/a	n/a	n/a
Computer-Aided Civil and Infrastructure Engineering	1	1935	5.288	0.003670
Concurrent Engineering Research and Applications	11	362	1.020	0.000350
Electronic Journal of Knowledge Management	1	n/a	n/a	n/a
Engineering Applications of Artificial Intelligence	1	3775	2.368	0.008720
Engineering with Computers	1	647	1.460	0.001520
IEEE Transactions on Engineering Management	2	2003	1.454	0.002290
IEEE Transactions on Systems, Man and Cybernetics, Part B (Cybernetics)	1	n/a	6.220	0.018300
IEEE Transactions on Systems, Man, and Cybernetics: Systems	1	3462	1.598	0.007240
IEEJ Transactions on Fundamentals and Materials	1	n/a	n/a	n/a
International Journal of Advanced Manufacturing Technology	3	12461	1.568	0.022400
International Journal of Computer Integrated Manufacturing	3	1141	1.319	0.001820
International Journal of Operational Research	1	n/a	n/a	n/a
International Journal of Product Development	3	n/a	n/a	n/a
Journal of Cleaner Production	1	19373	4.959	0.027930
Journal of Engineering Design	3	844	1.946	0.001280
Journal of Intelligent Manufacturing	1	2217	1.995	0.003920
Journal of Manufacturing Technology Management	1	n/a	n/a	n/a
Journal of Materials Processing Technology	1	21071	2.359	0.016430
Journal of Mechanical Design, Transactions of the ASME	2	4470	1.444	0.005730
Journal of the Chinese Institute of Industrial Engineers	1	n/a	n/a	n/a
Manufacturing Engineer	1	n/a	n/a	n/a
Marine Technology	1	n/a	n/a	n/a
Mechanical Engineering	1	665	0.271	0.000560
Naval Engineers Journal	3	201	0.157	0.000220
Nihon Kikai Gakkai Ronbunshu, C Hen/Transactions of the Japan Society of Mechanical Engineers, Part C	1	n/a	n/a	n/a
Organization Science	1	13837	3.360	0.024270
SAE Technical Papers	1	n/a	n/a	n/a
Sloan Management Review	2	1667	2.114	0.002960

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Table 2. (continued)

Strojniski Vestnik/Journal of Mechanical Engineering	1	388	0.677	0.001080
Structural and Multidisciplinary Optimization	1	3896	2.208	0.009480
Systems Engineering	1	455	0.956	0.000530
Transactions of the ASME. Journal of Manufacturing Science and Engineering	1	n/a	n/a	0.003000
WSEAS Transactions on Business and Economics	2	n/a	n/a	n/a
WSEAS Transactions on Fluid Mechanics	1	n/a	n/a	n/a
Total	61			
CA-A Cancer Journal for Clinicians	Ref. Max	20488	131.723	0.062610
Science of Nature	Ref. Min	13	0.000	0.000000

Six articles (Terwiesch, Loch & Meyer 2002; Ong *et al.* 2003; Nahm & Ishikawa 2006*a*,*b*; Wasim *et al.* 2013; de Souza & Borsato 2016) of the overall pool are published in journals with high Total Cites, (i.e., Organization Science, Journal of Material Processing Technology, Journal of Cleaner Production and the International Journal of Advanced Manufacturing Technology). In addition, a noticeable number of publications come from journals with relatively high Total Cites, which potentially indicates an increasing relevance of the research on SBCE and LPD. This, however, cannot be confirmed on the sole basis of the Total Cites as many other fields are published by the same journal and the Total Cites applies to all publications by the journal.

The average Impact Factor of the journals including the publications in the pool of relevant research is relatively low, which is quite representative of the field of design and product development research. However, Concurrent Engineering Research and Applications, which is the journal with most (11) of the 61 journal publications, is ranked 12th in the Computer, Database and Information Technology category. Similarly, Sloan Management Review is ranked 11th in the Management, Business, Decision Science and Finance category, while IEEE Engineering Management Review is in the top 100 of the same category (81st). Similarly, the International Journal of Advanced Manufacturing Technology is ranked 20th in the Mechanical, Production, Design, Automobile, Aeronautical and Industrial Engineering category. These results denote an extended breadth of SBCE research as it appears in several influential journals across different domains. It should be noted that the Impact Factor is an indicator of how many citations an article receives on average when published in a journal (Fersht 2009), which is in correlation with either the number of readers of the journal or the quality of the content or both. It is not possible to distinguish the impact of SBCE publications as compared to other publications of the same journal when it comes to the journal Impact Factor. However, it is possible to infer a potential visibility, importance and interest being given to SBCE research. The Eigenfactor Score similarly attempts to rate the influence of scientific journals by counting the number of citations a journal receives in a year and then weighing them based on the importance of the journal with the incoming citation (Bergstrom 2007). As seen in Table 2, the results are very similar to Total Cites, which is in line with the predicted strong correlation between Eigenfactor Scores and the total number

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of citations received by a journal (Fersht 2009). Therefore, conclusions similar to Total Cites apply.

5. Results from content analysis

This section focuses on the 24 publications in category 5, which are those related to the development of SBCE theories, models and methodologies aimed at practical implementation. The publications are listed in Table 3. The table is sorted by year of publication.

Table 3. Category 5 SBCE publications

Author	Title	Year	Source
(Levandowski, Müller & Isaksson 2016)	Modularization in concept development using functional modelling	2016	Advances in Transdisciplinary Engineering
(Araci, Al-Ashaab & Maksimovic 2016)	Knowledge Creation and Visualization by Using Trade-off Curves to Enable Set-based Concurrent Engineering	2016	Electronic Journal of Knowledge Management
(Al-Ashaab *et al.* 2016)	Development and application of lean product development performance measurement tool	2016	International Journal of Computer Integrated Manufacturing
(Raudberget, Michaelis & Johannesson 2014)	Combining set-based concurrent engineering and function-Means modelling to manage platform-based product family design	2014	IEEE International Conference on Industrial Engineering and Engineering Management
(Levandowski, Michaelis & Johannesson 2014)	Set-based development using an integrated product and manufacturing system platform	2014	Concurrent Engineering Research and Applications
(Ghosh & Seering 2014)	Set-based thinking in the engineering design community and beyond	2014	Proceedings of the ASME international design engineering technical conferences and computers and information in engineering conference, 2014
(Al-Ashaab *et al.* 2013)	The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry	2013	Concurrent Engineering Research and Applications
(Kerga, Taisch & Terzi 2013)	Set-based concurrent engineering innovation roadmap	2013	IFIP Advances in Information and Communication Technology

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Table 3. (continued)

(Michaelis, Levandowski & Johannesson 2013)	Set-based concurrent engineering for preserving design bandwidth in product and manufacturing system platforms	2013	ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)
(Levandowski *et al.* 2013)	Using PLM and trade-off curves to support set-based convergence of product platforms	2013	Proceedings of the International Conference on Engineering Design, ICED
(Khan *et al.* 2011)	Set-based concurrent engineering process within the LeanPPD environment	2011	Advanced Concurrent Engineering
(Raudberget 2011)	Enabling set-based concurrent engineering in traditional product development	2011	ICED 11–18th International Conference on Engineering Design – Impacting Society Through Engineering Design
(Avigad & Moshaiov 2009)	Set-based concept selection in multi-objective problems involving delayed decisions	2010	Journal of Engineering Design
(Inoue *et al.* 2010)	Design support system by combination of 3D-CAD and CAE with preference set-based design method	2010	Concurrent Engineering Research and Applications
(Shahan & Seepersad 2010)	Implications of alternative multilevel design methods for design process management	2010	Concurrent Engineering Research and Applications
(Parrish *et al.* 2008*b*)	Value propositions for set-based design of reinforced concrete structures	2008	Proceedings of IGLC16: 16th Annual Conference of the International Group for Lean Construction
(Nahm & Ishikawa 2006*a*)	A new 3D-CAD system for set-based parametric design	2006	International Journal of Advanced Manufacturing Technology
(Nahm & Ishikawa 2006*b*)	Novel space-based design methodology for preliminary engineering design	2006	International Journal of Advanced Manufacturing Technology
(Sobek *et al.* 1999)	Toyota's principles of set-based concurrent engineering	1999	Sloan Management Review
(Sobek 1996*a*)	Set-based model of design	1996	Mechanical Engineering
(Sobek 1996*b*)	Set-based model of design: the case of Toyota	1996	American Society of Mechanical Engineers (Paper)
(Liker *et al.* 1996)	Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering	1996	IEEE Transactions on Engineering Management

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Table 3. (continued)

(Ward *et al.* 1995)	The 2nd Toyota Paradox – how delaying decisions can make better cars faster	1995	Sloan Management Review
(Ward *et al.* 1994)	Set-based concurrent engineering and Toyota	1994	American Society of Mechanical Engineers, Design Engineering Division (Publication) DE

The first part of the synthesis examines the relationships between these contributions by using the proposed classification framework. The last part discusses the contributions in more detail by following a succession of epochs centred on the formulation of the Second Toyota Paradox by Ward *et al.* (1995).

5.1. Classification by research paradigms/methods

The chart in Figure 7 displays the distribution of research paradigms and methods related to the publications in the category of interest.

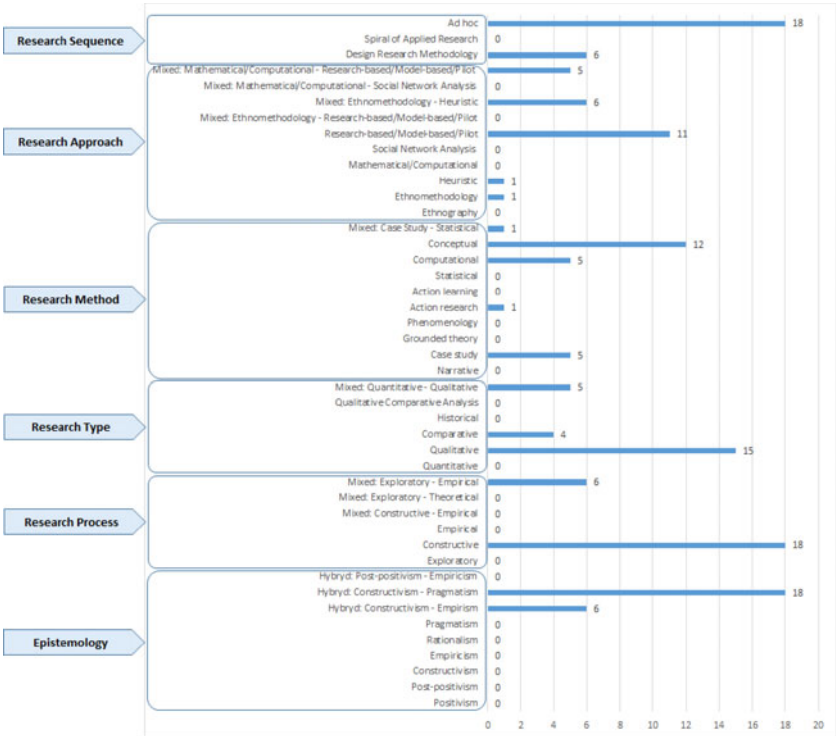

Figure 7. Distribution of the publications by research paradigms/methods.

The majority of publications in category 5 suggests a constructivist–pragmatist stance (75%), which denotes a field in active construction with common

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ground assumptions, principles and philosophy, shared and accepted within the community and believed to be further theorized through reasoning, experience and research. Knowledge in the SBCE and LPD community is viewed as a social construction (the community of SBCE and LPD researchers), and the foundational theories and principles are consistently rooted to the same landmark research effort, which in turn accounts for the rather constructivist–empiricist stance (25%) taken while studying Toyota and the Japanese automakers.

SBCE research is marked by enquiries into the interdisciplinary interactions within the design and product development process in context-specific settings. This is done in order to discover and understand the enablers and catalysts of the practice of SBCE. SBCE research is therefore predominantly qualitative and inductive, proceeding through natural enquiries. Data are expressed in the form of words rather than numbers, but quantitative analysis is often used to support experimental and computational methods, determine causality or to simply make sense of the data in order to generalize findings and extrapolate to similar situations. Qualitative coding (Strauss & Corbin 1990) is frequently used to segment the data into categories that facilitate in-depth understanding, comparison and the development of the SBCE theory. Comparative research is applicable to the foundational research work that formulated the SBCE concepts through the benchmarking, study and comparison of the world automakers. These researchers mainly performed case studies, which allowed them to understand the 'How' and 'Why' from the natural settings of actual SBCE practitioners. Indeed, the formulation of the Second Toyota Paradox by Ward *et al.* (1995) is a key milestone in SBCE research as it actually epitomized and coined the approach. Based on this evolution, there are necessarily themes and ideas that are not explicitly associated with these authors' designation but which might disclose characteristics of the same and, therefore, would actually improve its understanding and implementation. The remaining portion of the publications is theoretical, conceptual and computational by nature, proceeding through research-based, model-based and pilot research to either generate a theory of SBCE or confirm/improve one constructed so far. There is one action research performed in civil engineering (construction industry), which also accounts for the one purely ethnomethodology-based approach reported in the chart. The benchmarking and comparative studies performed by the foundational research work is, by contrast, regarded as mixing ethnomethodology and heuristic. From a research sequence standpoint, the large part of the focused publications (75%) follows ad hoc sequences with respect to the scientific method. The remaining part displays a preference for the Design Research Methodology (DRM) by Blessing & Chakrabarti (2009). This could reflect a recent influence of the DRM on the study of SBD at the atomic student project level rather than at a potentially larger integrated research programme level (count zero for the Spiral of Applied Research).

5.2. Classification by design process/methods

The chart in Figure 8 shows the distribution of the publications in category 5 by segments of the proposed classification framework.

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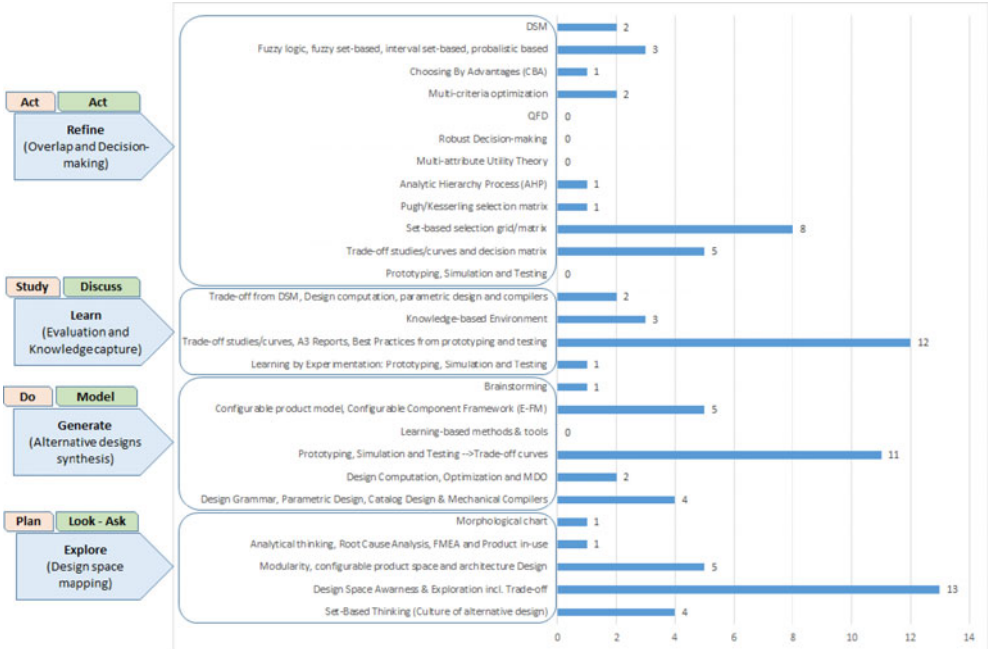

Figure 8. Distribution of the publications by design process/methods.

The initial phase of the SBCE process is sometimes achieved by merely considering multiple alternatives long into the design process and without resorting to any specific technique. This SBCE culture of alternative design exploration is a common practice in engineering design (Hubka & Eder 1987; Cross 1989; Pugh 1991; Wheelwright & Clark 1992; Baxter 1995; Ullman 2009; Ulrich & Eppinger 2012; Pahl & Beitz 2013), and it does not necessarily distinguish SBCE from the other PD paradigms. In practice, it is the time and effort spent handling, exploring and documenting multiple alternatives long into the development process that makes SBCE different. Four of the 24 publications in category 5 simply discuss this vision and practice during the PD process (Liker *et al.* 1996; Al-Ashaab *et al.* 2013, 2016; Ghosh & Seering 2014).

Design space awareness and exploration extend the vision by enabling the broad discovery of the design space to avoid narrowing too quickly on discrete areas of the space and thereby losing the potential for innovation and discovery. Engineering design books and textbooks also advocate the practice using a variety of knowledge-based tools and techniques, but it appears that there is a focus on trade-off studies within the SBCE literature, particularly trade-off curves (Maksimovic *et al.* 2012; Araci *et al.* 2016). This can be explained by a desire to explore and formalize Toyota's practice of SBCE as described by the foundational literature on SBCE (Ward *et al.* 1994; Sobek & Ward 1996; Sobek 1996*b*). The majority ($\geqslant$60%) of the publications in category 5 advocate exploring the design space, generating solutions and learning either by using computational tools (design grammars, parametric design, catalogue design and mechanical compilers) (Nahm & Ishikawa 2006*a*,*b*; Parrish *et al.* 2008*b*; Avigad & Moshaiov 2010; Inoue *et al.* 2010; Shahan & Seepersad 2010) or developing trade-off curves through prototyping, simulation and testing during one or more of the three

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phases (Ward *et al.* 1994, 1995; Liker *et al.* 1996; Sobek 1996*a*,*b*; Sobek *et al.* 1999; Khan *et al.* 2011; Raudberget 2011; Al-Ashaab *et al.* 2013; Levandowski *et al.* 2013; Michaelis *et al.* 2013; Levandowski *et al.* 2014; Al-Ashaab *et al.* 2016; Araci *et al.* 2016).

From a product platform design standpoint, modularity, architecture design and the configurable product space (bandwidth) are also advocated within the SBCE literature, as valid means to explore the design space and generate viable alternative designs (Levandowski *et al.* 2013, 2014, 2016; Michaelis *et al.* 2013; Raudberget *et al.* 2014). The CC framework and Enhanced Function Means (E-FM) modelling by Johannesson & Claesson (2005) are used there as the backbone to enable the approach during the product platform design.

The refinement phase of the SBCE process consists of overlapping alternative options from the disciplines and functional domains and making decisions to eliminate unfeasible designs. Overlapping the range options from many different views is generally perceived as complex and difficult to achieve, and researchers typically put forward trade-off studies, curves, generic decision matrices and set-based selection grids and matrices for communicating and eliminating alternatives (Sobek *et al.* 1999). The matrices use technical and other qualitative aspects/criteria of a design from different domains' perspectives in order to weigh and assess the feasibility and performance of the design.

The next section will analyse the contributions on the development of SBCE theories, models and methodologies for SBCE included in category 5 in more detail. The discussion is organized in a succession of epochs presented to render the evolution of themes, ideas and experiences towards the formulation and refinement of the SBCE philosophy, principles, models and methodologies.

5.3. Before the Toyota Paradox

As previously mentioned, set-based reasoning and methods existed before the publication of the Second Toyota Paradox. These early 90s' research efforts in engineering design calculations involved set-based reasoning by using fuzzy parameters, labelled interval calculus and other methods like the MoI and constraint satisfaction (Antonsson & Wood 1989; Tommelein 1989; Ward 1989; Hyvönen 1992; Wood *et al.* 1992; ElMaraghy & Jack 1993; Hernandez-Luna & Wood 1994). However, they did not entail the holistic SBCE philosophy, principles and the institutional knowledge capture and reuse advocated, enabling a superior PD process as encapsulated in the Second Toyota Paradox (Ward *et al.* 1995). In addition, these early research efforts involving set-based methods were not always nominally identified as such, which is the reason why some may not be retrieved by keyword searches with the term 'set-based'. This area of publication as discussed here is discovered through reference backtracking with the purpose of understanding what set-based thinking was about before the Second Toyota Paradox and the origination of the term 'set-based concurrent engineering'. For instance, Ward initially developed a theory of quantitative inference for artefact sets applied to design compilers, in particular, mechanical design compilers. The software construct used a schematic and high-level labelled interval specification language to allow a mechanical designer to search for an optimal design through a component database. The search then returned appropriate catalogue numbers of the granular components and progressively narrowed them until an overall cost function was fulfilled. The theory and the

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resulting software implementation represented and manipulated sets of artefacts at operating conditions rather than a single artefact under a single operating condition. Moreover, it performed searches by progressively narrowing volumes of the artefact space rather than searching point to point in that space. The theory and its implementation really correspond to SBD as it was later formulated by the author. Another example of set-based reasoning (applied to a design process before the Second Toyota Paradox) is the work done by Tommelein in structural engineering. Tommelein (1989) used a set-based methodology to generate adequate construction site layouts by reasoning about spatial constraints that need to be satisfied between rectangular sets in a layout. The approach was implemented in the SightPlan software, which is based on the Blackboard (BB1) architecture for combining geometry under constraints and displaying emerging solutions without committing to a specific one (Tommelein 1989). From a similar perspective, Antonsson and Wood stressed uncertainty and the fuzzy nature of specifications and requirements during the design by formulating the design problem in terms of fuzzy parameters and constraints. In their method, they generate a range of possible design variable values (fuzzy sets of design) using the fuzzy set method of imprecision. This method resolves the design variable values by mapping the design preference onto the performance space while also quantifying imprecision (Antonsson & Wood 1989; Wood *et al.* 1992; Hernandez-Luna & Wood 1994). Other methods preceding the Second Toyota Paradox include the use of Boolean equations (ElMaraghy & Jack 1993) or interval arithmetic (Hyvönen 1992) to resolve design problems and potentially communicate between disciplines (e.g., design–manufacturing) via a range of parameter values rather than a single value at a time.

5.4. The Second Toyota Paradox

Set-based concurrent engineering, as it refers to Toyota's practice, was coined by Ward *et al.* (1994) in their landmark paper presented at the proceedings of the 1994 ASME Design Technical Conferences in Minneapolis, USA. The paper presents a new paradigm for concurrent or simultaneous design. The new paradigm is based on apparent paradoxes in Toyota Motor Company's new product development strategies. Evidence from various interviews with the U.S. and Japanese automakers and automotive parts suppliers is presented, including two in-depth case studies. The paper concludes with a discussion of the potential benefits of this new paradigm. The paradigm was then extended in an article published the following year in the MIT Sloan Management Review (Ward *et al.* 1995). According to the authors, the First Toyota Paradox is Toyota's lean production system as it involves unusual practices compared to traditional mass production. The article introduces the reader to the Second Toyota Paradox, which is basically the SBCE paradigm. The paradox is expressed by means of delaying decisions, communicating about the range of possibilities and pursuing apparently excessive numbers of prototypes. These elements taken together form the way by which Toyota is believed to design better cars faster and cheaper than its competitors. The authors explain that in their practice of SBCE, Toyota's engineers 'intuitively' distinguish between cases requiring broad design space exploration as opposed to cases where a narrow, more constrained search is suitable; they later described how to make this determination formally based on the type of development project (Ward & Sobek 2014). The SBCE

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characteristics, techniques and advantages are explained, emphasizing a process that relies on handling and narrowing sets of possible solutions through design space exploration, prototyping, learning and commitment to robustness, all this by using effective management practices and the chief engineer concept. Many detailed examples of SBCE interactions among Toyota's functional disciplines are discussed and also Toyota's SBCE interactions with its suppliers. Examples of the joint practice of SBCE with key partner Nippon Denso are provided. The authors conclude with the prediction that 'companies adopting concurrent engineering through cross-functional teams and a structured development process that focus on designing the right product in the concept stage will inevitably move in the direction of set-based concurrent engineering' (Ward *et al.* 1995).

Sobek (1996*a*) further advocates the SBCE process in a paper published in the Mechanical Engineer. The author argues that engineers can find better designs quicker by designing and developing sets of alternatives and then continually communicating about the available options rather than pursuing a single option at a time. SBCE is presented as the application of SBD to parallel development (in reference to CE, i.e., concurrent engineering), with five typical activities: global exploration, space expansion, parallel narrowing, conceptual robustness and pre-design. Many characteristics and advantages of SBD are also explained including the chief engineer role, prototyping and testing, individual and organizational learning, communication about sets of design and design spaces and commitment after establishing feasibility and global optima rather than independently optimized components.

In a search of evidence of SBCE, Liker et al. investigated 92 Japanese and 119 US automotive parts suppliers, with the purpose of determining the prevalence of set-based approaches in each group based on predefined indicators (Liker *et al.* 1996). The outcome of the survey evidenced that SBD communication was more prevalent among Japanese suppliers than among their U.S. counterpart. Set-based CE is contrasted in the article with traditional CE by emphasizing the need for a paradigm shift in order to operate an effective, truly concurrent engineering. The SBCE paradigm is discussed in detail, explaining the difference with traditional CE when it comes to communicating requirements, exploring the solution space, communicating about designs (product or manufacturing process) by using ranges, gradually narrowing ranges, using parallel approaches, a large number of prototypes and by exploring trade-offs. The effect of the suppliers' involvement early in the design process and the correlation with the use of set-based techniques is explored, concluding that there is a strong positive correlation between the two. Another correlation that is explored is the relationship between the use of set-based techniques and the degree to which product and process design overlaps, which surprisingly concludes on a weak correlation. Component interdependence and the use of Quality Function Deployment (QFD) are also considered set-based indicators, and they are equally explored in relation to the practice of SBCE among the groups. The two indicators display strong associations with SBD practices. The authors believe that the SBD philosophy has the potential to 'provide high-bandwidth, trustworthy, and useful information creation and transmission' processes. As such, these authors stress important implications of set-based CE, which include: (1) going slow early in the process and developing a large number of alternatives that allow for faster downstream design with less rework cycles; (2) developing new vocabularies for participants to communicate

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in sets; (3) switching organizational mindset to think in terms of narrowing sets rather than iterating on one single solution; (4) reconsidering the use of CAD systems early in the design process as they force commitment to many specific design decisions; and finally (5) potentially reducing the need for frequent face-to-face communication. Further research is recommended by the authors to develop indicators and metrics for point-based versus set-based design more carefully. The authors highlight the fact that the list of set-based indicators used in the survey is not exhaustive and that it should not be considered perfect either. According to the authors, the theories, the principles and basically what are the essential elements of SBCE should be better studied and formalized in order to perform accurate measures of the set-based culture of an organization.

Following the recommendations from Liker *et al.* (1996), Sobek *et al.* (1999) published an article in the MIT Sloan Management Review in which they elaborated on Toyota's principles of SBCE. The article describes the SBCE paradigm and its main characteristics as opposed to the traditional point-based approach. Three principles underlying SBCE are synthesized and presented as follows. (1) Map the design space. (Define feasible regions. Explore trade-offs by designing multiple alternatives. Communicate sets of possibilities.) (2) Integrate by intersection. (Look for intersections of feasible sets. Impose minimum constraint. Seek conceptual robustness.) (3) Establish feasibility before commitment. (Narrow sets gradually while increasing detail. Stay within sets once committed. Control by managing uncertainty at process gates.) The set-based communication and evaluation process is discussed using, for example, a matrix of alternatives including strengths and weaknesses with regard to the governing evaluation criteria. The convergence process is also presented focusing on a discipline groundwork (called Nemawashi), which for each discipline is about consistently finding the best solutions for the overall system under minimum constraints. The set-based selection process is explained in terms of narrowing sets gradually while increasing details but no formal approach, technique or tool is presented to support the overlapping of independent range solutions/alternatives that lead to discarding unfeasible designs. The SBCE principles combined with a culture of continuous creation of organizational knowledge appear to form the basis of the superior development system. It is argued that any organization that can implement these principles, as well as the related culture of organizational knowledge, may radically improve their design and development processes. Further study of the causality of the predicted outcomes/effects with regard to the synthesized SBCE principles is however prompted.

In essence, the authors who participated in formulating the Second Toyota Paradox collectively recommended further studies of the causal relationship between Toyota's success and its practice of SBCE. The authors acknowledged that SBCE, as described, was the result of their perception of a system that is not explicitly documented or known to be well understood and performed in a systematic way. They, therefore, prompted researchers to construct the methodologies of SBCE and test them in other organizations in order to formulate a complete theory of SBD.

5.5. The post-Second Toyota Paradox publication

As a way to follow up on recommendations from the SBCE landmark research, the post-Second Toyota Paradox research efforts are usually performed outside

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the context of Toyota or any SBCE-proven Japanese entity, but at the same time, by quite systematically leveraging the philosophy, theories and principles developed while formulating the Second Toyota Paradox. This is to say, the SBCE philosophy, theories and principles as discussed above are collectively accepted, not reconsidered but rather studied and implemented in a constructivist–pragmatist way in order to confirm the premises or formulate a more complete theory of SBD. For example, although Liker et al. indicated that the use of CAD systems early in the design process should be reconsidered as they force commitment to many specific design decisions, Nahm, Ishikawa and Inoue (Nahm & Ishikawa 2006*a*,*b*; Inoue *et al.* 2010) pragmatically leverage advances in CAD systems to propose a CAD-oriented SBD methodology that can support preliminary design activities and decisions. Indeed, the authors' research work is motivated by the limitations of the traditional CAD systems in (1) supporting the conceptual design stage with its design information scarceness and uncertainty and (2) handling non-geometrical information, which is complementary and necessary design information required to fully define an engineering artefact as well as linking the CAD systems with other engineering systems and CE processes. These authors' research is geared to provide a blend of methods and tools characterized by a parametric communication and robust design convergence process that use uncertain and incomplete information in support of the SBD paradigm. Their work combines SBD with the parametric modelling technique available in the geometric modelling kernels of most of the CAD systems. The combination produces a new concept called set-based parametric design (SBPD) for which a preference set-based design (PSD) model and a design information solid (DIS) model are proposed to ease the incorporation of the SBPD concept into the current CAD systems. Simply put, the DIS model augments the CAD data structure by adding non-geometrical design information as attribute data of the boundary representation (B-Reps) of the solid models (Nahm & Ishikawa 2006*a*). It then becomes possible to store qualitative information such as functions, design intent, applicability, materials, context domain information, e.g., assemblability data, search index strings, etc. A designer working with a parametric solid model may populate the geometrical and non-geometrical parameter data and constraints, which will later be scanned by the PSD model when exploring the design space. The PSD model is a set-to-set mapping that propagates a designer preference sets (input) onto the available rich parametric solid models, given the constraints, so as to explore the interval sets and produce outputs under design information uncertainty (Nahm & Ishikawa 2006*a*). The PSD is a hybrid model that combines the Antonsson & Wood (1989) fuzzy set-based MoI with the Finch & Ward (1997) interval set-based approach (which in turn is made up of the Quantified Relations (QRs) and the interval propagation theorem (IPT) algorithm). To exemplify their approach, Nahm and Ishikawa present a prototype system implementation that uses the PARASOLID CAD kernel to illustrate both the feasibility of the DIS model and the robustness of a PSD processor while propagating, aggregating, modifying and narrowing interval sets in order to infer solution sets (Nahm & Ishikawa 2006*a*). The research work of Nahm, Ishikawa and Inoue is essentially motivated by the need to develop space representation methods, space mapping methods and space narrowing methods in support of the effective implementation of SBCE. These authors discuss a new space-oriented design methodology, which is based on interval sets and preference functions defined on the sets.

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The approaches used for processing the intervals include decomposed fuzzy arithmetic, extended interval arithmetic, i.e., IPT, Design of Experiment (DoE) and a new design metric called preference and robustness index (PRI). The combination of the approaches and metrics allows for a set-to-set mapping from a design space to a performance space and subsequently narrowing of the interval sets to eliminate unfeasible subspace solutions (Nahm & Ishikawa 2006*a*,*b*; Inoue *et al.* 2010). Following their research, Nahm and Ishikawa recommend that future research should pay more attention to the data-level, interface-level, and application-level integration of heterogeneous 3D-CAD systems as well as the collaboration/interoperability required between CAx tools (Nahm & Ishikawa 2006*a*). Some limitations regarding the proposed PSD model are also highlighted, which mainly consist of the inability of the model to produce correct output intervals for some combinations of input intervals. The limitation is thought to be caused by the direct use of IPT. Further research is required to allow checking the appropriateness of an input set in order to avoid the designer's trial-and-error procedure, which may become painful while searching for a correct input interval.

Another noticeable post-Second Toyota Paradox research effort is the research done at Cranfield University by Al-Ashaab, Shehab, Khan, Araci, Maksimovic, et al. mostly under the FP7 Theme 4 of the 2009–2013 Lean Product and Process Development (LeanPPD) European research programme. These authors' research is essentially motivated by the lack of formal SBCE methodology or process that can guide the systematic implementation of lean PD (Khan *et al.* 2011; Khan 2012; Al-Ashaab *et al.* 2013, 2016; Khan *et al.* 2013; Araci *et al.* 2016). In Khan *et al.* (2011), Khan (2012), SBCE is advocated as the keystone of lean PD, and five principles describing SBCE are synthesized from a literature review. These principles are similar to Sobek *et al.* (1999) principles with the addition of Morgan, Liker and Ward principles for classifying development projects according to the company's value strategy in relation to the customer value (Morgan & Liker 2006; Ward & Sobek 2014). A 'set-based concurrent engineering baseline model' is introduced by describing a stage-gate process through which alternative solutions are collected, narrowed into a set of solutions and converged onto an optimal solution before commencing the detailed design. Pugh matrices are used for the selection process. The model as presented and implemented is rather point-based, which limits its application for an SBD perspective. This is also pointed out by Raudberget (2015, p. 26), citing Al-Ashaab *et al.* (2013). In addition, there is no provision for a potential design or product model that could support the communication, narrowing, overlapping and refinement of sets. Furthermore, the iterative learning capability, which is central to SBCE and LPPD, is missing. However, Khan (2012) stresses the ability of the proposed model to enable SBCE and justifies the point-based outcomes of the thesis's two pilot case studies by the inherent time and resource constraints in industrial product development projects. The constraints, in the case of the author's pilot simulations, led to pressurized, non-informed and subjective decision-making (Khan 2012, p. 184). In all cases, Khan *et al.* note that SBCE research should focus on developing models that can support the communication, narrowing, overlapping and refinement of sets and, furthermore, research should focus on enabling the iterative learning capability, which is central to SBCE and lean PD (Khan *et al.* 2011, 2013).

Drawing upon previous groundwork, Al-Ashaab *et al.* (2016) discuss the development of an LPD performance measurement tool to assess the 'leanness' of

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a PD process. In recognizing that SBCE is the core component of LPPD, the authors devise an assessment tool that relies on the enablers of a 'LeanPPD' model and the principles of SBCE, as synthesized from the literature by Khan *et al.* (2011, 2013). The tool supports assessing a company's practice of SBCE and LPPD from four perspectives (Al-Ashaab *et al.* 2016): (1) product development process, i.e., directly referring to the practice of SBCE and the presence of the chief engineer and value focus enablers; (2) tools and enablers (as collected by Khan et al.) regarding lean and SBCE; (3) knowledge focus, which is key to lean, i.e., knowledge-based environment to support the capture, storage, retrieval, communication and the institutional learning as advocated by Ward & Sobek (2014); and finally (4) continuous improvement as a means for the tool to both express an as-is state and then drive to a to-be state implementation roadmap. The authors propose an assessment scale named SAUCE (Start-Awareness-Unstructured-Continued-Evolved) to allow a visual representation of a company's current 'leanness' state, which also is an incentive to devise an improvement plan to reach the next level. The scale is non-cyclic (with reference to continuous improvement tools like PDSA, DMAIC, LAMDA), but it supports improvement towards the desired state. Regardless, assessments are performed in two companies in the aerospace and the automotive industry, with the intent of demonstrating the ability of the measurement tool and the scale to provide insights into a company's practice of lean PD and SBCE in a systematic way. Indeed, the research developed on a tool to assess the lean PD and SBCE practice of a company based on enablers in the 'LeanPPD' model, as well as principles of SBCE as synthesized from the literature. However, the research did not discuss approaches, methodologies or frameworks that can actually support the lean transformation within an organization. This is seen as research opportunities by the authors. Other publications by the same authors focus on more specific SBCE enablers by attempting to develop upon such techniques and practices. For example, Araci *et al.* (2016) concentrate on the use of trade-off curves (ToC) to enable SBCE and LPPD, by proposing a process for generating and leveraging knowledge-based and math-based ToCs at each stage of the 'set-based concurrent engineering baseline model' described by Khan (2012). While these authors deepen the understanding and applicability of a well-known SBCE enabler (Sobek *et al.* 1999; Ward & Sobek 2014), they rely on the SBCE baseline model that was previously criticized for its point-based approach (Raudberget 2015, p. 26). In addition, it is unclear how sets of design are composed, overlapped, narrowed and eliminated by using ToCs from different functional groups. Maulana *et al.* (2016) potentially fill this gap in their application of SBCE to enhance the design performance of a surface jet pump. These authors first develop conceptual sets by using ToCs, stakeholders' expertise and brainstorming. Then they eliminate unfeasible sets by leveraging an Analytical Hierarchy Process (AHP) (Saaty 1990), which is fed by data gathered from prototyping and testing, i.e., CFD simulations and past project data. Al-Ashaab *et al.* (2013) also use AHP in the same vein. They describe a transformation process towards LPD in a company. The transformation consists of two stages whereby the first infuses the principles of SBCE (Khan *et al.* 2013) into an existing product development process by introducing the relevant lean activities and tools (e.g., QFD, brainstorming, DoE, Pugh matrix, AHP, FMEA, risk analysis, etc.) in a timely manner. The second stage infers a generic model for

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structuring activities and tools for the desired type of transformation to achieve lean PD. This is applied to a research-based case study. Although the results can be viewed as linked to a particular development context, they provide some guidelines on how to restructure existing PD activities and appropriately use SBCE principles and tools to transition to a lean PD. This again is a blend of activities, tools and techniques that implements an approach or so-called SBCE process, which does not rely on the well-defined model of SBCE. That is, one that is in the continuum of a design process model, product model or knowledge-based model with the aim of federating the three Ps (People–Product–Process) towards SBCE and LPD in traditional industrial contexts.

A potentially advanced model and practical approach to SBCE can be found in the research work done at the Department of Product and Production Development of Chalmers University of Technology (Michaelis *et al.* 2013; Levandowski 2014; Raudberget 2015). These authors leverage the CC framework and Enhanced Function Means (E-FM) modelling by Johannesson & Claesson (2005) to enable SBCE during product platform design. The related manufacturing process design is also considered. Configurability is perceived and advocated as a fundamental means to handle multiple design alternatives, allow mapping, exploring the design space and gradually narrowing sets while preserving the design bandwidth, i.e., decision delay. The design bandwidth concept is equivalent to the viable, flexible solution sets that represent architectural options from which a coherent product design can be extracted, instantiated and passed onto downstream processes for further design and validation (Berglund & Claesson 2005). E-FM modelling presents the advantage of spanning the functional (FRs) and technological/physical (DSs) domains, which allows for variability both at the functional requirement level and the logical system design level, i.e., functional feature. It is not always easy to understand the difference and interaction between the CC framework and the E-FM modelling. The CC framework is essentially meant to encapsulate a system level design variability and thereby bridge the gap between the technological domain (DSs) and the physical domain (Parts) where applicable. To achieve this, the CC framework is built upon configuration rules for Part selection from catalogues, which allows for combining variability in the technological and functional domains with variability in the physical domain. The purpose is to translate architectural options into various workable product variants. Indeed, an instantiation input (design parameters) is usually passed to the CC framework, which may then extract a specific physical design variant based on the system level architecture it has inherited from the E-FM tree (Johannesson & Claesson 2005). Johannesson and Claesson mention that the information technology necessary to deploy the framework is commercially available in Product Data Management (PDM) systems such as iMAN from EDS PLM Solutions, which is now part of the Siemens PLM software, i.e., Teamcenter. Indeed, the E-FM and CC framework show core similarities with product models usually deployed in industrial PLM software but they also display a good compatibility with SBCE. For instance, Michaelis, Levandowski and Raudberget leverage the combinatorial effects of variability and configurability within the E-FM and CC framework to advocate the fair compatibility with SBCE design space exploration. These authors use variability within the E-FM tree model to handle multiple architectural options that can then be analysed with the purpose of reducing functional design

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solution couplings, and then progressively eliminate unfeasible designs at the conceptual level (Michaelis *et al.* 2013; Levandowski 2014; Raudberget 2015). This is also seen as extendable to manufacturing processes (Levandowski *et al.* 2014; Johannesson & Claesson 2005). The framework allows for SBCE convergence processes because it supports (1) the exploration of a product platform design space as well as the elimination of unfeasible designs and (2) the preservation of conceptual solution sets until variants are instantiated through the CC framework for embodiment design and a reality check. Although the framework shows capabilities at the conceptual level, it remains unclear how the functional groups (i.e., requirements engineering, advanced engineering, systems engineering, components engineering, etc.) may interact using it. To cite Johannesson & Claesson (2005), the corresponding development approach that relates to the framework and fully exploits it remains unclear, i.e., the complete development process. The lifecycle stages beyond conceptual design are rarely addressed, which results in less substance when it comes to the SBCE front-loading process, reusable design knowledge management, prototyping and testing for an informed convergence process, value streams' cross-functional interactions and, basically, the remaining SBCE means by which a product platform can be developed in a large-scale industrial conventional PD framework and lean context. Levandowski *et al.* (2013) attempt to fill these gaps by exploring an approach whereby product variants are instantiated from the CC modeller and then passed to a PLM software to engage downstream activities in the development process. Virtual prototyping and simulations are performed through the normal PLM process and then trade-off curves are produced to inform the E-FM/CC platform design by means of an analog feedback, which then helps the product platform design convergence process. This approach discloses dislocated methodologies and tools that may foster scatter, hand-offs and waste. The same approach and gaps are present in Johannesson *et al.* (2017). Since product modelling and configurable product models span multiple product development stages and domains (i.e., functional, technological, physical processes) (Wortmann & Erens 1995; Erens 1996; Andreasen, Hansen & Mortensen 1996; Männistö *et al.* 2001; Huet *et al.* 2011; Toche *et al.* 2012), it is argued by Toche (2017) that their ability to enable SBCE can be explored from a holistic PD perspective and by using a continuum of tools and methodology as they pertain to large-scale industrial conventional PD supporting frameworks such as PDM (including configuration management) and PLM. Similarly, although Digital Mock-ups (DMU), Functional DMU (FDMU) and industrial DMU (iDMU) extensively support the conventional industrial PDP (Lazzari & Raimondo 2001; Drieux 2006; Garbade & Dolezal 2007; Enge-Rosenblatt *et al.* 2011; Herlem *et al.* 2012; Mas *et al.* 2014), the prototyping (virtual and physical) and testing (including simulations) phases are also rarely used as actual means to enable the SBCE overlapping and decision-making process. These are all aspects that require more evaluation in future research.

Other significant post-Second Toyota Paradox research includes contributions from Parrish et al., Kerga, Taisch and Terzi, Avigad and Moshaiov, as well as Shahan and Seepersad. Parrish et al. explored the benefits of implementing SBCE during the design of reinforced concrete structures (Parrish *et al.* 2008*a*; Parrish 2009). Variability is considered in these authors' contributions. Alternative design solutions are explored by using Building Information Modelling (BIM), which is similar to PLM in many aspects (Jupp 2016). Parrish (2009) emphasizes

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stakeholders' interaction while communicating, postponing and deciding about sets of design. This author proposes a comparative study of a variety of decision-making processes/methods, ranging from Robust Decision-making (Ullman 2001), Multi-attribute Utility Theory (Thurston 1990), AHP (Saaty 1990) to Choosing By Advantages (CBA) (Suhr 1999), to name a few. Parrish in her dissertation thesis states that 'literature cannot prescribe a set of steps to implement an SBD process since it is context-specific. It varies with the stakeholders involved, the design phase, the decision unit, and the project itself' (Parrish 2009, p. 266). A manifestation of this can be found in Kerga *et al.* (2014*a*), where trade-off curves are perceived as detrimental to the set-based innovation process in serious games. The theory of inventive problem solving (TRIZ) is proposed as an improved methodological approach while implementing SBCE. However, the performance gained compared to the use of trade-off curves is not explained. From another perspective, Avigad & Moshaiov (2010) propose an approach to delay conceptual decisions under uncertainty while maintaining and assessing the performance of multiple design concepts. This is done by translating the design problem into a multi-objective problem and by mapping each of the design concepts to a cluster of points in the objective space, representing the discrete option performances (Avigad & Moshaiov 2010). The approach requires abstracting the design problem into a design space tree (i.e., *Complete Concept* tree) and then an objective and variability space. The authors argue that when achieved properly, the approach may allow comparing design concepts based on their robustness, i.e., sensitivity to change according to the delayed decisions' uncertainty. This approach is relevant to SBCE during the design conceptual phase. It requires several levels of abstraction and computations that are not easy to position in the context of an industrial SBCE implementation.

The remaining part of the post-Second Toyota Paradox research usually consists of confirmatory studies of the SBCE performance using computational simulations or pilot projects. For example, Shahan & Seepersad (2010) use multi-criteria optimization and discrete event simulations to explore the effects of highly iterative exchanges of single design solutions (point-based) versus minimally iterative exchanges of multiple solutions (set-based) on the overall lead time of a design process. These authors conclude in favour of the reduced overall iteration cycles (hence shorter lead times) in SBCE as well as the robust convergence in the case of flexible, optimal size, rich and less frequent exchanges of information. These findings are similar to those by Beauregard *et al.* (2014). They are also consistent with the findings by Ford & Sobek (2005) with regard to their assessment of the development project performance in set-based versus point-based using real option valuation models. As their simulations were done on serialized processes, Shahan & Seepersad (2010) point out the necessity to investigate concurrent processes in the context of available computer-aided engineering tools, product lifecycle management and knowledge-based engineering capabilities.

6. Conclusions and perspectives

A critical literature review of SBD was carried out in this article by following an evidence-based procedure to analyse the literature. The objective of the review was to find answers to the following questions:

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(i) *What is the state of the art of SBD literature?*
(ii) *What are the most important contributions to the SBD focusing on the development of a model and methodology?*
(iii) *What are the key aspects to consider when developing such a model and methodology?*

A classification and review of the most relevant contributions pertaining to the objectives were performed. The discussion allowed us to discover and explore themes and ideas connected to the key aspects to consider when developing models and methodologies intended to support a transition to SBCE.

From a broad perspective, the relatively low theoretical development of SBD, combined with a steady increase of the diversity of contributions since 2010, suggests a growing visibility, importance and interest being given to SBD from a variety of research fields. This progression might be interpreted as a manifestation of the Ward *et al.* (1995) prediction that 'companies adopting concurrent engineering through cross-functional teams and a structured development process that focus on designing the right product in the concept stage will inevitably move in the direction of set-based concurrent engineering'.

From the synthesis, it is possible to articulate a number of findings and research opportunities. First, the authors who participated in formulating the Second Toyota Paradox collectively recommended further study of the causal relationship between Toyota's success and its practice of SBCE. These authors acknowledged the fact that SBCE, as described, was the result of their perception of a system that was not explicitly documented or known to be well understood and performed in a systematic way. Therefore, they prompted researchers to construct the methodologies of SBCE and test them in other organizations in order to formulate a complete theory of SBD. It is also found from the synthesis that research is required to extend the application of SBD theories and principles beyond the conceptual design stage, especially implications for detailed design, prototyping, testing and the rest of the product development cycle. In more detail, the product development stages beyond conceptual design are rarely addressed within the SBD literature. Research is required to better address the SBCE front-loading process, the reusable design knowledge management, prototyping and testing (for an informed convergence process), the value streams' cross-functional interactions and, basically, the means by which a product platform can be developed in a large-scale lean industry conventional PD framework by implementing SBCE. Indeed, SBD authors consistently agree on the lack of holistic models that can support the cross-domain communication, overlapping, narrowing, and refinement of sets to enable the iterative institutional learning capability that is core to SBCE and LPD. To continue with the findings, product structuring, configurability and variability emerged from the synthesis as effective SBCE enablers. However, they remain scarce within the SBD literature. Their ability to enable SBCE is not explored from a holistic PD perspective and by using a continuum of tools and methodology as they pertain to large-scale industrial conventional PD supporting frameworks. Another aspect of SBD that requires more study is the practice of prototyping and testing and the relationship with the overall design process. Extensive prototyping and testing is key to SBD in order to foster the knowledge-based environment, the institutional learning capability and, therefore, accurately inform the decision-making process. Although this is frequently portrayed in the literature, the existing industrial

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design prototyping (virtual and physical) frameworks are rarely connected with SBCE. More specifically, the effects of major SBCE enablers (e.g., product structuring, configurability, prototyping, set-based selection process etc.) on the development process performance are rarely studied, whether by experimenting alternative hypotheses or disproving the null hypothesis. New approaches are required to explore additional themes and ideas that are not explicitly associated with SBD but which share characteristics of the same and, therefore, have the potential to improve its understanding and implementation. Overall, the discovery and study of the key aspects to consider when developing a model and methodology to transition to SBCE should be extended by finding, and empirically assessing, the compatibility and confluence between the themes. This is the subject of ongoing research by the authors.

References

Al-Ashaab, A., **Golob, M.**, **Attia, U. M.**, **Khan, M.**, **Parsons, J.**, **Andino, A.**, **Perez, A.**, **Guzman, P.**, **Onecha, A.** & **Kesavamoorthy, S.** 2013 The transformation of product development process into lean environment using set-based concurrent engineering: a case study from an aerospace industry. *Concurrent Engineering* **21**, 268–285.

Al-Ashaab, A., **Golob, M.**, **Urrutia, U. A.**, **Gourdin, M.**, **Petritsch, C.**, **Summers, M.** & **El-Nounu, A.** 2016 Development and application of lean product development performance measurement tool. *International Journal of Computer Integrated Manufacturing* **29**, 342–354.

Andreasen, M. M., **Hansen, C. T.** & **Mortensen, N. H.** 1996 The structuring of products and product programmes. In *DS 53: Proceedings of the 2nd WDK Workshop on Product Structuring*. Delft University of Technology.

Antonsson, E. K. & **Otto, K. N.** 1995 Imprecision in engineering design. *Journal of mechanical design* **117**, 25–32.

Antonsson, E. K. & **Wood, K. L.** 1989 Computations with imprecise parameters in engineering design: background and theory. *ASME Journal of Mechanisms, Transmissions and Automation in Design* **111**, 616–625.

Araci, Z. C., **Al-Ashaab, A.** & **Maksimovic, M.** 2015 A process of generating trade-off curves to enable set-based concurrent engineering. In *Proceedings of the 16th European Conference on Knowledge Management: ECKM 2015* **(ed. M. Massaro & A. Garlatti)**. University of Udine, Italy Academic Conferences and publishing limited.

Araci, Z. C., **Al-Ashaab, A.** & **Maksimovic, M.** 2016 Knowledge creation and visualisation by using trade-off curves to enable set-based concurrent engineering. *Electronic Journal of Knowledge Management* **14**, 75–88.

Augustine, M., **Yadav, O. P.**, **Jain, R.** & **Rathore, A. P. S.** 2010 Concept convergence process: a framework for improving product concepts. *Computers & Industrial Engineering* **59**, 367–377.

Avigad, G. & **Moshaiov, A.** 2009 Set-based concept selection in multi-objective problems: optimality versus variability approach. *Journal of Engineering Design* **20**, 217–242.

Avigad, G. & **Moshaiov, A.** 2010 Set-based concept selection in multi-objective problems involving delayed decisions. *Journal of Engineering Design* **21**, 619–646.

Baines, T., **Lightfoot, H.**, **Williams, G. M.** & **Greenough, R.** 2006 State-of-the-art in lean design engineering: a literature review on white collar lean. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **220**, 1538–1547.

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Baxter, M. 1995 *Product Design: A Practical Guide to Systematic Methods of New Product Development*. Chapman & Hall.

Beauregard, Y., **Bhuiyan, N.** & **Thomson, V.** 2014 Lean engineering performance analysis. *International Journal of Product Development* **19**, 366–387.

Becker, J. M. J. & **Wits, W. W.** 2015 Enabling lean design through computer aided synthesis: the injection moulding cooling case. In *4th CIRP Global Web Conference*. Elsevier.

Berglund, F. & **Claesson, A.** 2005 Utilising the concept of a design's bandwidth to achieve product platform effectiveness. In *Proceedings of the 15th International Conference on Engineering Design, ICED 05, Melbourne, Australia*. The Design Society, ISBN 0-85825-788-2.

Bergstrom, C. 2007 Eigenfactor: measuring the value and prestige of scholarly journals. *C&RL News* **68**, 314–316.

Bernstein, J. 1998 Design methods in the aerospace industry: looking for evidence of set-based practices. Master thesis, Massachusetts Institute of Technology.

Bertoni, A., **Levandowski, C.**, **Isaksson, O.** & **Larsson, T.** 2016 Virtual Modeling for Lifecycle Performance Assessment in aerospace design. *Procedia CIRP* **47**, 335–340.

Blessing, L. T. M. & **Chakrabarti, A.** 2009 *DRM, A Design Research Methodology*. Springer.

Browning, T. R. 2000 Value-based product development: refocusing lean. In *Proceedings of the 2000 IEEE Engineering Management Society, EMS – 2000*. IEEE.

Camburn, B. A., **Arlitt, R.**, **Perez, K. B.**, **Anderson, D.** & **Kun, P.** 2017 Design prototyping of systems. In *Proceedings the 21st International Conference on Engineering Design, ICED 2017, Vancouver, BC, Canada*. The Design Society, ISBN 978-1-904670-89-6.

Camburn, B. A., **Dunlap, B.**, **Gurjar, T.**, **Hamon, C.**, **Green, M.**, **Jensen, D.**, **Crawford, R.**, **Otto, K.** & **Wood, K.** 2015 A systematic method for design prototyping. *Journal of Mechanical Design* **137**, 08110201–08110212.

Canbaz, B., **Yannou, B.** & **Yvars, P.-A.** 2011 A new framework for collaborative set-based design: application to the design problem of a hollow cylindrical cantilever beam. In *Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2011, Washington, DC, USA*. American Society of Mechanical Engineers.

Canbaz, B., **Yannou, B.** & **Yvars, P.-A.** 2014 Improving process performance of distributed set-based design systems by controlling wellbeing indicators of design actors. *Journal of Mechanical Design, Transactions of the ASME* **136**, 021005.

Cho, Y. S., **Lee, S. I.** & **Bae, J. S.** 2014 Reinforcement placement in a concrete slab object using structural building information modeling. *Computer-Aided Civil and Infrastructure Engineering* **29**, 47–59.

Claesson, A. 2006 A configurable component framework supporting platform-based product development. PhD thesis, Chalmers University of Technology.

Claesson, A. & **Johannesson, H.** 2006 Integrated and configurable product and manufacturing models. In *Proceedings of the 9th International Design Conference, DESIGN 2006, Dubrovnik, Croatia*. The Design Society.

Clark, K. B. & **Fujimoto, T.** 1991 *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry*. Harvard Business School Press.

Cross, N. 1989 *Engineering Design Methods*. Wiley.

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de Souza, V. M. & **Borsato, M.** 2016 Combining Stage-Gate^{TM} model using Set-Based concurrent engineering and sustainable end-of-life principles in a product development assessment tool. *Journal of Cleaner Production* **112**, 3222–3231.

Deming, W. E. 2000 *The New Economics: For Industry, Government, Education*. MIT Press.

Drieux, G. 2006 De la maquette numérique produit vers ses applications aval: propositions de modèles et procédés associés – from the product digital mock-up to its downstream applications: a proposal of models and their associated processes (In French). Doctoral dissertation, INPG.

Elhariri Essamlali, M. T., **Sekhari, A.** & **Bouras, A.** 2017 Product lifecycle management solution for collaborative development of Wearable Meta-Products using set-based concurrent engineering. *Concurrent Engineering* **25**, 41–52.

ElMaraghy, W. H. & **Jack, H.** 1993 Facilitating rapid product realization with a high-level CAPP system. In *Proceedings of the IFIP TC5/WG5. 3 Conference on Towards World Class Manufacturing 1993*. North-Holland Publishing Co.

Enge-Rosenblatt, O., **Clauß, C.**, **Schneider, A.** & **Schneider, P.** 2011 Functional digital mock-up and the functional mock-up interface-two complementary approaches for a comprehensive investigation of heterogeneous systems. In *Proceedings of the 8th International Modelica Conference*. Technical University, Linköping University Electronic Press.

Erens, F. 1996 The synthesis of variety: developing product families. PhD thesis, Technische Universiteit Eindhoven, The Netherlands.

Essamlali, M. T. E., **Sekhari, A.** & **Bouras, A.** 2016 PLM system support for collaborative development of wearable meta-products using SBCE. In *Proceedings of the 12th IFIP WG 5.1 International Conference on Product Lifecycle Management in the Era of Internet of Things, PLM 2015*. Springer.

Fersht, A. 2009 The most influential journals: impact factor and eigenfactor. *Proceedings of the National Academy Sciences* **106**, 6883–6884.

Finch, W. W. & **Ward, A. C.** 1997 A set-based system for eliminating infeasible designs in engineering problems dominated by uncertainty. In *Proceedings of the 1997 ASME Design Engineering Technical Conferences, DETC97, Sacramento, CA, USA*. American Society of Mechanical Engineers.

Ford, D. N. & **Sobek, D. K.** 2005 Adapting real options to new product development by modeling the second Toyota paradox. *IEEE Transactions on Engineering Management* **52**, 175–185.

Garbade, R. & **Dolezal, W.** 2007 DMU@ airbus – evolution of the digital mock-up (DMU) at airbus to the centre of aircraft development. In *Proceedings of the 17th CIRP Design Conference. User Keynote, the Future of Product Development* **(ed. F.-L. Krause)**. Springer.

Gericke, K., **Eckert, C.** & **Stacey, M.** 2017 What do we need to say about a design method? In *Proceedings of the 21st International Conference on Engineering Design, ICED 17*. The Design Society.

Ghosh, S. & **Seering, W.** 2014 Set-based thinking in the engineering design community and beyond. In *Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2014*. American Society of Mechanical Engineers.

Giachetti, R. E. 1997 Manufacturing process and material selection during conceptual design. *Industrial Engineering Research – Conference Proceedings* **47250**, 772–777.

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Hannapel, S. & **Vlahopoulos, N.** 2014 Implementation of set-based design in multidisciplinary design optimization. *Structural and Multidisciplinary Optimization* **50**, 101–112.

Hannapel, S. E., **Vlahopoulos, N.** & **Singer, D. J.** 2012 Including principles of set-based design in multidisciplinary design optimization. In *Proceedings of the 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*. American Institute of Aeronautics and Astronautics Inc.

Hart, C. 1998 *Doing a Literature Review: Releasing the Social Science Research Imagination*. Sage.

Hegge, H. 1995 Intelligent product family descriptions for business applications: production control software based upon generic bills-of-material in an assemble-to-order/make-to-stock environment. PhD thesis, Technische Universiteit Eindhoven, The Netherlands.

Heikkinen, T., **Stolt, R.**, **Elgh, F.** & **Andersson, P.** 2016 Automated producibility assessment enabling set-based concurrent engineering. In *Proceedings of the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering*. IOS Press.

Herlem, G., **Adragna, P.-A.**, **Ducellier, G.** & **Durupt, A.** 2012 DMU Maturity Management as an Extension of the Core Product Model. In *Product Lifecycle Management: Towards Knowledge-rich Enterprises, Proceedings of IFIP WG 5.1 International Conference, PLM 2012* **(ed. L. Rivest, A. Bouras & B. Louhichi)**. Springer.

Hernandez-Luna, A. A., **Moreno-Grandas, D. P.** & **Wood, K. L.** 2010 Trade-off of fuzzy set-based design parameters. In *Proceedings of the IIE Annual Conference and Expo 2010*. Institute of Industrial Engineers.

Hernandez-Luna, A. A. & **Wood, K. L.** 1994 A set based concurrent engineering method for parameter design. In *Proceedings of the 7th International Symposium on Artificial Intelligence*. Inst. Technol. Estudios Superiores de Monterrey.

Hoepfl, M. C. 1997 Choosing qualitative research: a primer for technology education researchers. *Journal of Technology Education* **9**, 47–63.

Hoppmann, J., **Rebentisch, E.**, **Dombrowski, U.** & **Zahn, T.** 2011 A framework for organizing lean product development. *Engineering Management Journal* **23**, 3–15.

Howard, T. J., **Culley, S. J.** & **Dekoninck, E.** 2008 Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies* **29**, 160–180.

Hubka, V. & **Eder, W. E.** 1987 A scientific approach to engineering design. *Design Studies* **8**, 123–137.

Huet, G., **Fortin, C.**, **McSorley, G.** & **Toche, B.** 2011 The management of manufacturing processes using complementary information structures. In *Proceedings of the 18th International Conference on Engineering Design, ICED'11, Copenhagen, Denmark*. The Design Society.

Hyvönen, E. 1992 Constraint reasoning based on interval arithmetic: the tolerance propagation approach. *Artificial Intelligence* **58**, 71–112.

Inoue, M., **Lindow, K.**, **Stark, R.**, **Tanaka, K.**, **Nahm, Y.-E.** & **Ishikawa, H.** 2012 Decision-making support for sustainable product creation. *Advanced Engineering Informatics* **26**, 782–792.

Inoue, M., **Nahm, Y.-E.**, **Okawa, S.** & **Ishikawa, H.** 2010 Design support system by combination of 3D-CAD and CAE with preference set-based design method. *Concurrent Engineering* **18**, 41–53.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

Inoue, M., **Nahm, Y.-E.**, **Tanaka, K.** & **Ishikawa, H.** 2013*a* Collaborative engineering among designers with different preferences: application of the preference set-based design to the design problem of an automotive front-side frame. *Concurrent Engineering Research and Applications* **21**, 252–267.

Inoue, M., **Nahm, Y.-E.**, **Tanaka, K.** & **Ishikawa, H.** 2013*b* Decision-making support for selection of design ideas at the early phase of structural design. In *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment* **(ed. J. Stjepandi , G. Rock & C. Bil)**. Springer.

Ishikawa, H. & **Inoue, M.** 2009 Set-based FEM for product design with uncertainties. In *Proceedings of the ASME 2009 International Mechanical Engineering Congress and Exposition (IMECE2009)*. American Society of Mechanical Engineers.

Ishikawa, H. & **Nahm, Y.-E.** 2005 Set-based design methodology and its application to design of automobile body. In *Proceedings of the 12th ISPE International Conference on Concurrent Engineering: Research and Applications – Next Generation Concurrent Engineering: Smart and Concurrent Integration of Product Data, Services, and Control Strategies, CE 2005*. International Society for Pharmaceutical Engineering.

Johannesson, H. & **Claesson, A.** 2005 Systematic product platform design: a combined function-means and parametric modeling approach. *Journal of Engineering Design* **16**, 25–43.

Johannesson, H., **Landahl, J.**, **Levandowski, C.** & **Raudberget, D.** 2017 Development of product platforms: theory and methodology. In *Concurrent Engineering*, vol. 25, pp. 195–211.

Jupp, J. R. 2016 Cross industry learning: a comparative study of product lifecycle management and building information modelling. *International Journal of Product Lifecycle Management* **9**, 258–284.

Kawakami, M., **Kami, Y.**, **Ishikawa, H.** & **Xiao, F.** 2016 Application of the preference set-based design method to filter design. *IEEJ Transactions on Fundamentals and Materials* **136**, 621–628.

Kennedy, B. M., **Sobek, D. K.** & **Kennedy, M. N.** 2014 Reducing Rework by Applying Set-Based Practices Early in the Systems Engineering Process. *Systems Engineering* **17**, 278–296.

Kennedy, M. N. 2003 *Product Development for the Lean Enterprise: Why Toyota's System is Four Times More Productive and How You Can Implement It*. Oaklea Press.

Kerga, E., **Khan, M. S.** & **Arias, A. B.** 2012*a* Advanced process planning in lean product and process development. In *Proceedings of the 18th International Conference on Engineering, Technology and Innovation, ICE 2012*. IEEE.

Kerga, E., **Rossi, M.**, **Taisch, M.** & **Terzi, S.** 2014*a* A serious game for introducing set-based concurrent engineering in industrial practices. *Concurrent Engineering Research and Applications* **22**, 333–346.

Kerga, E., **Rossi, M.**, **Terzi, S.**, **Taisch, M.**, **Bessega, W.** & **Rosso, A.** 2014*b* Teaching set-based concurrent engineering to practitioners through gaming. *International Journal of Product Development* **19**, 348–365.

Kerga, E., **Taisch, M.** & **Terzi, S.** 2012*b* Manufacturing process planning in set-based concurrent engineering paradigm. In *Product Lifecycle Management: Towards Knowledge-rich Enterprises. Proceedings of IFIP WG 5.1 International Conference, PLM 2012* **(ed. L. Rivest, A. Bouras & B. Louhichi)**. Springer.

Kerga, E., **Taisch, M.** & **Terzi, S.** 2013 Set based concurrent engineering innovation roadmap. In *Proceedings of the IFIP WG 5.7 International Conference, APMS 2013, Advances in Production Management Systems. Sustainable Production and Service Supply Chains* **(ed. V. Prabhu, M. Taisch & D. Kiritsis)**. Springer.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

Khan, M. S. 2012 The construction of a model for lean product development. PhD thesis, Cranfield University.

Khan, M. S., **Al-Ashaab, A.**, **Doultsinou, A.**, **Shehab, E.**, **Ewers, P.** & **Sulowski, R.** 2011 Set-based concurrent engineering process within the LeanPPD environment. In *Improving Complex Systems Today: Proceedings of the 18th ISPE International Conference on Concurrent Engineering* **(ed. D. D. Frey, S. Fukuda & G. Rock)**. Springer.

Khan, M. S., **Al-Ashaab, A.**, **Shehab, E.**, **Haque, B.**, **Ewers, P.**, **Sorli, M.** & **Sopelana, A.** 2013 Towards lean product and process development. *International Journal of Computer Integrated Manufacturing* **26**, 1105–1116.

Kizer, J. R. & **Mavris, D. N.** 2014 Set-based design space exploration enabled by dynamic constraint analysis. In *Proceedings of the 29th Congress of the International Council of the Aeronautical Sciences, ICAS 2014*. International Council of the Aeronautical Sciences.

Landahl, J., **Levandowski, C.**, **Johannesson, H.** & **Isaksson, O.** 2016 Assessing producibility of product platforms using set-based concurrent engineering. In *Proceedings of the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering* **(ed. M. Borsato, N. Wognum, M. Peruzzini, J. Stjepandi & W. J. C. Verhagen)**. IOS Press.

Landahl, J., **Raudberget, D.** & **Johannesson, H.** 2015 Assessing system maturity of interacting product and manufacturing alternatives before early technology commitment. In *Proceedings of the 24th International Association for Management of Technology Conference, IAMOT 2015*. International Association for Management of Technology (IAMOT).

Lazzari, D. & **Raimondo, G.** 2001 Digital mock-up in support to space station elements integration and test. In *Proceedings of the 4th International Symposium on Environmental Testing for Space Programmes,* vol. 467. European Space Agency.

León, H. C. M. & **Farris, J. A.** 2011 Lean product development research: current state and future directions. *Engineering Management Journal* **23**, 29–51.

Levandowski, C. 2014 Platform lifecycle support using set-based concurrent engineering. PhD thesis, Chalmers University of Technology.

Levandowski, C., **Forslund, A.**, **Söderberg, R.** & **Johannesson, H.** 2013 Using PLM and trade-off curves to support set-based convergence of product platforms. In *Proceedings of the 19th International Conference on Engineering Design, ICED 2013, Seoul, Korea (South)*. The Design Society.

Levandowski, C., **Michaelis, M. T.** & **Johannesson, H.** 2014 Set-based development using an integrated product and manufacturing system platform. *Concurrent Engineering* **22**, 234–252.

Levandowski, C., **Müller, J. R.** & **Isaksson, O.** 2016 Modularization in concept development using functional modeling. In *Proceedings of the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering*. IOS Press.

Liker, J. K., **Sobek Ii, D. K.**, **Ward, A. C.** & **Cristiano, J. J.** 1996 Involving suppliers in product development in the United States and Japan: evidence for set-based concurrent engineering. *IEEE Transactions on Engineering Management* **43**, 165–178.

Maksimovic, M., **Al-Ashaab, A.**, **Sulowski, R.** & **Shehab, E.** 2012 Knowledge visualization in product development using trade-off curves. In *Proceedings of the 2012 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2012*. IEEE.

Männistö, T., **Peltonen, H.**, **Soininen, T.** & **Sulonen, R.** 2001 Multiple abstraction levels in modelling product structures. *Data & Knowledge Engineering* **36**, 55–78.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

Mas, F., **Menendez, J. L.**, **Oliva, M.**, **Rios, J.**, **Gomez, A.** & **Olmos, V.** 2014 iDMU as the collaborative engineering engine: research experiences in airbus. In *Proceedings of the 20th International Conference on Engineering, Technology and Innovation: Engineering Responsible Innovation in Products and Services, ICE 2014*. IEEE.

Matthews, J., **Klatt, T.**, **Seepersad, C. C.**, **Haberman, M.** & **Shahan, D.** 2014 Bayesian network classifiers and design flexibility metrics for set-based, multiscale design with materials design applications. In *Proceedings of the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2014*. American Society of Mechanical Engineers.

Maulana, M. I. I. M., **Flisiak, J. W.**, **Al-Ashaab, A.**, **Araci, Z. C.**, **Lasisz, P. W.**, **Beg, N.** & **Rehman, A.** 2016 The application of set-based concurrent engineering to enhance the design performance of surface jet pump. *WSEAS Transactions on Business and Economics* **13**, 634–643.

McKenney, T. & **Singer, D.** 2014 Set-based design: a concurrent engineering approach with particular application to complex marine products. *Marine Technology* **51**, 51–55.

McKenney, T. A., **Gray, A. W.**, **Madrid, C.** & **Singer, D. J.** 2011*a* The use of a fuzzy logic set-based design tool to evaluate varying complexities of late-stage design changes. In *Proceedings of the 2011 International Conference on Computer Applications in Shipbuilding*. Royal Institution of Naval Architects.

McKenney, T. A., **Kemink, L. F.** & **Singer, D. J.** 2011*b* Adapting to changes in design requirements using set-based design. *Naval Engineers Journal* **123**, 66–77.

McManus, H. L., **Haggerty, A.** & **Murman, E.** 2005 Lean engineering: doing the right thing right. In *1st International Conference on Innovation and Integration in Aerospace Sciences*. Queen's University Belfast.

Michaelis, M. T., **Levandowski, C.** & **Johannesson, H.** 2013 Set-based concurrent engineering for preserving design bandwidth in product and manufacturing system platforms. In *Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition, IMECE2013*. American Society of Mechanical Engineers.

Morgan, J. M. & **Liker, J. K.** 2006 *The Toyota Product Development System: Integrating People, Process, and Technology*. Productivity Press.

Moshaiov, A. & **Avigad, G.** 2007 Concept-based multi-objective problems and their solution by EC. In *Proceedings of the 9th Annual Genetic and Evolutionary Computation Conference, GECCO 2007*. Association for Computing Machinery.

Nahm, Y.-E. & **Ishikawa, H.** 2005 Representing and aggregating engineering quantities with preference structure for set-based concurrent engineering. *Concurrent Engineering Research and Applications* **13**, 123–133.

Nahm, Y.-E. & **Ishikawa, H.** 2006*a* A new 3D-CAD system for set-based parametric design. *The International Journal of Advanced Manufacturing Technology* **29**, 137–150.

Nahm, Y.-E. & **Ishikawa, H.** 2006*b* Novel space-based design methodology for preliminary engineering design. *The International Journal of Advanced Manufacturing Technology* **28**, 1056–1070.

Nahm, Y.-E., **Ishikawa, H.** & **Yang, Y.-S.** 2007 A flexible and robust approach for preliminary engineering design based on designer's preference. *Concurrent Engineering* **15**, 53–62.

Neeley, W. L., **Lim, K.**, **Zhu, A.** & **Yang, M. C.** 2013 Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design. In *Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2013*. American Society of Mechanical Engineers.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

NHS 2001 Undertaking systematic reviews of research on effectiveness: CRD's guidance for carrying out or commissioning reviews, University of York, UK, NHS Centre for Reviews and Dissemination (CRD).

Nissen, M. E. 1996 A focused review of the reengineering literature: expert frequently asked questions (FAQs). *Quality Management Journal* **3**, 52–66.

Oehmen, J. & **Rebentisch, E.** 2010 Waste in lean product development. LAI Paper Series "Lean Product Development for Practitioners". Lean Advancement Initiative (LAI), Massachusetts Institute of Technology.

Ong, S., **Sun, M.** & **Nee, A.** 2003 A fuzzy set AHP-based DFM tool for rotational parts. *Journal of Materials Processing Technology* **138**, 223–230.

Ong, S. K. & **Nee, A. Y. C.** 1998 A systematic approach for analyzing the fixturability of parts for machining. *Transactions of the ASME. Journal of Manufacturing Science and Engineering* **120**, 401–408.

Oppenheim, B. W. 2004 Lean product development flow. *Systems Engineering* **7**, 352–376.

Otto, K. N. & **Antonsson, E. K.** 1995 Imprecision in engineering design. *ASME Journal of Mechanical Design* **117**, 25–32.

Pahl, G. & **Beitz, W.** 2013 *Engineering Design: A Systematic Approach*. Springer Science & Business Media.

Panchal, J. H., **Gero Fernández, M.**, **Paredis, C. J.**, **Allen, J. K.** & **Mistree, F.** 2007 An interval-based constraint satisfaction (IBCS) method for decentralized, collaborative multifunctional design. *Concurrent Engineering* **15**, 309–323.

Parrish, K. D. 2009 Applying a set-based design approach to reinforcing steel design. PhD thesis, University of California.

Parrish, K. D., **Wong, J.-M.**, **Tommelein, I. D.** & **Stojadinovic, B.** 2008*a* Set-based design: case study on innovative hospital design. In *16th Annual Conference of the International Group for Lean Construction (IGLC 16), Manchester, UK*.

Parrish, K. D., **Wong, J. M.**, **Tommelein, I. D.** & **Stojadinovic, B.** 2008*b* Value propositions for set-based design of reinforced concrete structures. In *Proceedings of the 16th Annual Conference of the International Group for Lean Construction, IGLC16, Manchester, England*. University of Salford.

Pourabdollahian, B., **Taisch, M.** & **Kerga, E.** 2012 Serious games in manufacturing education: evaluation of learners' engagement. *Procedia Computer Science* **15**, 256–265.

Pugh, S. 1991 *Total Design: Integrated Methods for Successful Product Engineering*. Addison-Wesley.

Qureshi, A. J., **Dantan, J.-Y.**, **Bruyere, J.** & **Bigot, R.** 2010 Set based robust design of mechanical systems using the quantifier constraint satisfaction algorithm. *Engineering Applications of Artificial Intelligence* **23**, 1173–1186.

Qureshi, A. J., **Dantan, J.-Y.**, **Bruyere, J.** & **Bigot, R.** 2014 Set-based design of mechanical systems with design robustness integrated. *International Journal of Product Development* **19**, 64–89.

Raudberget, D. S. 2010*a* The decision process in set-based concurrent engineering-an industrial case study. In *Proceedings of the 11th International Design Conference, DESIGN 2010, Dubrovnik, Croatia*. The Design Society.

Raudberget, D. S. 2010*b* Practical applications of set-based concurrent engineering in industry. *Journal of Mechanical Engineering* **56**, 685–695.

Raudberget, D. S. 2011 Enabling set-based concurrent engineering in traditional product development. In *Proceedings of the 18th International Conference on Engineering Design, ICED 11, Lyngby/Copenhagen, Denmark*.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

Raudberget, D. S. 2015 Industrial application of set-based concurrent engineering – managing the design space by using platform system families. PhD thesis, Chalmers University of Technology.

Raudberget, D. S., **Michaelis, M. T.** & **Johannesson, H.** 2014 Combining set-based concurrent engineering and function – means modelling to manage platform-based product family design. In *Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2014*. IEEE.

Raudberget, D. S. & **Sunnersjö, S.** 2010 Experiences of set based concurrent engineering in four product developing companies. In *Proceedings of the 8th International Symposium on Tools and Methods of Competitive Engineering, TMCE 2010, Ancona, Italy*. Delft University of Technology.

Rebentisch, E. 2008 Lean product development in the aerospace enterprise. In *Proceedings of the 26th Congress of the International Council of the Aeronautical Sciences, ICAS 2008, Anchorage, AK, USA*. International Council of The Aeronautical Sciences (ICAS).

Reinertsen, D. 2007 Rethinking lean NPD. *Strategic Directions* **23**, 32–34.

Rocha, H. M., **Affonso, L. M. F.** & **De Oliveira, U. L. R.** 2012 New product development using set-based concurrent engineering (SBCE). In *Decision Making Systems in Business Administration*. World Scientific Publishing.

Rocha, H. M., **Affonso, L. M. F.** & **De Oliveira, U. L. R.** 2013 Optimizing the set-based concurrent engineering (SBCE): new product development management decisions. In *Proceedings of the 22nd International Conference on Production Research (ICPR22), Iguassu Falls, Brazil*. S.I.

Saaty, T. L. 1990 How to make a decision: the analytic hierarchy process. *European Journal of Operational Research* **48**, 9–26.

Sabin, D. & **Weigel, R.** 1998 Product configuration frameworks-a survey. *IEEE Intelligent Systems and Their Applications* **13**, 42–49.

Sasaki, N. & **Ishikawa, H.** 2015 Set-based design method for multi-objective structural design with conflicting performances under topological change. *Procedia CIRP* **26**, 76–81.

Shahan, D. & **Seepersad, C. C.** 2009 Bayesian networks for set-based collaborative design. In *Proceedings of the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2009*. American Society of Mechanical Engineers.

Shahan, D. & **Seepersad, C. C.** 2010 Implications of alternative multilevel design methods for design process management. *Concurrent Engineering* **18**, 5–18.

Shahan, D. & **Seepersad, C. C.** 2012 Bayesian network classifiers for set-based collaborative design. *Journal of Mechanical Design, Transactions of the ASME* **134**, 0710011–07100114.

Shan, S. & **Wang, G. G.** 2003 Introducing rough set for design space exploration and optimization. In *Proceedings of the ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC 2003*. American Society of Mechanical Engineers.

Sobek, D. K. 1996*a* Set-based model of design. *Mechanical Engineering* **118**, 78–81.

Sobek, D. K. 1996*b* Set-based model of design: the case of Toyota. In *Proceedings of the 1996 National Design Engineering Conference*. American Society of Mechanical Engineers.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

Sobek, D. K. & **Ward, A. C.** 1996 Principles from Toyota's set-based concurrent engineering process. In *Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, DETC 1996*. American Society of Mechanical Engineers.

Sobek, D. K., **Ward, A. C.** & **Liker, J. K.** 1999 Toyota's principles of set-based concurrent engineering. *Sloan Management Review* **40**, 67–83.

Strauss, A. & **Corbin, J.** 1990 *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*. Sage Publications.

Suhr, J. 1999 *The choosing by advantages decisionmaking system*. Greenwood Publishing Group.

Takai, S. 2010 A lifecycle-cost model for set-based concept testing. *Concurrent Engineering* **18**, 121–127.

Terwiesch, C., **Loch, C. H.** & **Meyer, A. D.** 2002 Exchanging preliminary information in concurrent engineering: alternative coordination strategies. *Organization Science* **13**, 402–419.

Thurston, D. L. 1990 Multiattribute utility analysis in design management. *IEEE Transactions on Engineering Management* **37**, 296–301.

Toche, B. 2017 Set-based prototyping in the context of the configurable virtual product: the construction of the Learning Value Streams (LVS) model. PhD thesis, Polytechnique Montreal.

Toche, B., **Pellerin, R.**, **Fortin, C.** & **Huet, G.** 2012 Set-based prototyping with digital mock-up technologies. In *Product Lifecycle Management: Towards knowledge-rich enterprises. Proceedings of IFIP WG 5.1 International Conference, PLM 2012* **(ed. L. Rivest, A. Bouras & B. Louhichi)**. Springer.

Tommelein, I. D. 1989 SightPlan: an expert system that models and augments human decision-making for designing construction site layouts. PhD thesis, Stanford University.

Tranfield, D., **Denyer, D.** & **Smart, P.** 2003 Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management* **14**, 207–222.

Ullman, D. G. 2001 Robust decision-making for engineering design. *Journal of Engineering Design* **12**, 3–13.

Ullman, D. G. 2009 *The Mechanical Design Process*. McGraw-Hill Higher Education.

Ulrich, K. T. & **Eppinger, S. D.** 2012 *Product Design and Development*. McGraw-Hill Higher Education.

Van Veen, E. A. 1991 Modelling product structures by generic bills-of-materials. PhD thesis, Technische Universiteit Eindhoven.

Wahl, A. & **Johannesson, H.** 2010 Managing design change in configurable component based product platforms. In *Proceedings of the 8th International NordDesign Conference, NordDesign 2010, Göteborg, Sweden*. The Design Society.

Wang, G. G. & **Shan, S.** 2004 Design space reduction for multi-objective optimization and robust design optimization problems. In *Proceedings of the 2004 SAE World Congress*. SAE International.

Wang, J., **Yannou, B.**, **Alizon, F.** & **Yvars, P.-A.** 2013 A usage coverage-based approach for assessing product family design. *Engineering with Computers* **29**, 449–465.

Ward, A. C. 1989 A theory of quantitative inference for artifact sets applied to a mechanical design compiler. Doctor of Science Dissertation, Massachusetts Institute of Technology.

Downloaded from https://www.cambridge.org/core. IP address: 173.176.9.147, on 22 Oct 2021 at 14:20:03, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2020.16

Ward, A. C., **Liker, J. K.**, **Cristiano, J. J.** & **Sobek, D. K.** 1995 The second Toyota paradox: how delaying decisions can make better cars faster. *Sloan Management Review* **36**, 43–61.

Ward, A. C., **Liker, J. K.**, **Sobek, D. K.** & **Cristiano, J. J.** 1994 Set-based concurrent engineering and Toyota. In *Proceedings of the 6th International Conference on Design Theory and Methodology. 1994 ASME Design Technical Conferences*. American Society of Mechanical Engineers.

Ward, A. C. & **Sobek, D. K.** 2014 *Lean Product and Process Development*. The Lean Enterprise Institute.

Wasim, A., **Shehab, E.**, **Abdalla, H.**, **Al-Ashaab, A.**, **Sulowski, R.** & **Alam, R.** 2013 An innovative cost modelling system to support lean product and process development. *The International Journal of Advanced Manufacturing Technology* **65**, 165–181.

Wheelwright, S. C. & **Clark, K. B.** 1992 *Revolutionizing product development: quantum leaps in speed, efficiency, and quality*. The Free Press.

Wood, K. L., **Otto, K. N.** & **Antonsson, E. K.** 1992 Engineering design calculations with fuzzy parameters. *Fuzzy Sets and Systems* **52**, 1–20.

Wortmann, J. C. & **Erens, F.** 1995 Control of variety by generic product modeling. In *Proceedings of The First World Congress on Intelligent Manufacturing Processes and Systems, Puerto Rico, PR, USA*. University of Puerto Rico.

Yannou, B., **Yvars, P.-A.**, **Hoyle, C.** & **Chen, W.** 2013 Set-based design by simulation of usage scenario coverage. *Journal of Engineering Design* **24**, 575–603.

Zhai, L.-Y., **Khoo, L.-P.** & **Zhong, Z.-W.** 2009 A rough set based QFD approach to the management of imprecise design information in product development. *Advanced Engineering Informatics* **23**, 222–228.

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