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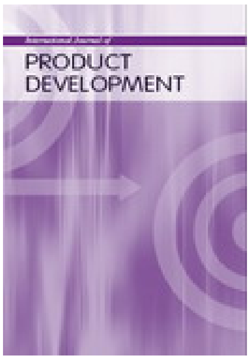

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Review of models and frameworks for set-based design

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Abstract: This paper aims to investigate the state-of-the-art in models and frameworks for set-based design and identify the main gaps and contributions in the literature. As a result, 121 models were analysed. Most models are quantitative, computational, engineering design-oriented and focus on early stages. Although the narrowing down process plays a central role in the set-based design, very little is addressed regarding its management processes. No model was found describing the inputs and outputs of the set-based design and the narrowing down process simultaneously. Thus, knowledge is dispersed and focused on specific parts. The relevance of this study relies on providing a comprehensive investigation of the state-of-the-art, identifying opportunities to advance in this study field and providing recommendations for future works seeking to support the development of new methods for implementing and managing set-based design, enabling and encouraging its adoption.

Keywords: set-based design; lean product development; literature review; narrowing down process; concurrent engineering; design space; value; trade-off; quality function deployment; integrated product teams.

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1 Introduction

Organisations are driven to be faster, more competitive and more innovative due to socioeconomic factors, which compel them to adopt even more lean initiatives, especially regarding product development. One can observe a growing interest in Set-Based Design (SBD) research since the number of publications has consistently increased over the years (Toche et al., 2020; Shallcross et al., 2020a; Dullen et al., 2021). Despite this scenario, the implementation of SBD is still being constructed with few studies providing a practical and detailed approach to its practices (Hoppmann et al., 2011; Leon and Farris, 2011; Toche, 2017; Tariq, 2018; Toche et al., 2020). Among the reasons that can be attributed to this are the lack of a consistent theoretical basis (Hoppmann et al., 2011; Toche et al., 2020) and the difficulties related to the organisational culture and other nuances that enable SBD (Ammar et al., 2017). This scenario does not favour its adoption. Even though its superiority over traditional product development approaches is known, its implementation is hampered by the absence of general, integrated, and wide guidelines for a well-established SBD.

To further advance knowledge in this field, this paper aims to investigate the state-of-the-art in models and frameworks for SBD, identifying the main gaps and contributions in the literature. Through a Systematic Bibliographic Review (SBR), 121 models were found and analysed. Although some reviews of the literature have been published in recent years (see Table 1) (Dullen et al., 2021; Shallcross et al., 2020a; Specking et al., 2018; Toche et al., 2020), none presents a review with such depth and extension, identifying gaps that may discourage SBD adoption, especially concerning its managerial aspects. The scope of the review by Specking et al. (2018) has a restricted focus on methods for set definition, elimination, and trade-off analytics. As a result, 34 papers with methods to define and eliminate sets were found and analysed. Dullen et al. (2021) reviewed 118 papers on quantitative methods to support the adoption of the SBD. They classified these methods into (1) Analytic Hierarchy Process (AHP), (2) Classification Methods (CM), (3) Constraint Satisfaction Problems (CSPs), (4) FLS, (5) MAUT, (6) Markov Decision Processes (MDP), (7) Multi-Objective Optimisation Methods (MOOM) and (8) Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The review performed by Shallcross et al. (2020a) analysed 122 papers seeking robust alternative development, uncertainty reduction and resolution, delayed design decisions, and effective design team communication. The authors sought to advance the adoption of SBD in complex systems development, expanding the search beyond SBD.

Table 1 Reviews on set-based design

	Specking et al. (2018)	*Shallcross et al. (2020a)*	*Toche et al. (2020)*	*Dullen et al. (2021)*	*This research*
Objective of the review	SBD research in methods for trade-off analytics	SBD state-of-practice, focusing on complex system design applications	SBD theories, models and methodologies for a practical implementation	Quantitative methods to support SBD	Models and frameworks for SBD
Period	1993–2017	1993–2019	1987–2017	1995–2020	1987–2021
Finding	34 methods for trade-off analytics	122 works for complex systems (SBD and others)	24 theories, models and methodologies for an SBD transition	118 quantitative methods for SBD	121 models and frameworks for SBD

Regarding the works from Specking et al. (2018); Shallcross et al. (2020a) and Dullen et al. (2021), this review is much wider and comprises all models and frameworks regardless of the environment, type of system or development stage. The review by Toche et al. (2020) aims to identify theories, models and methodologies for SBD in the literature. The author sought SBD theories, models and methods to support SBD, considering a wide scope, similar to this research. Nevertheless, this paper includes more recent literature on SBD since the bibliographic review made by Toche et al. (2020) contains works published before 2017. Furthermore, they analysed the content of 24 works whilst this research analyses 121 different models. This paper aims to pave the way for a comprehensive model for SBD, guiding the development of new methods to further advance knowledge in the field. Therefore, it is not appropriate to perform a limited review. It is necessary to carry out a complete scan of the literature so that a real overview of gaps can be obtained to foster the advancement of knowledge in the SBD. Therefore, the relevance of this study is to thoroughly scan the literature and determine which models were proposed for SBD, analyse and indicate the main knowledge gaps and research opportunities, denote the main contributions made in the literature and finally, provide recommendations for future works.

To better present the chain of ideas, this paper was structured first with a brief theoretical background of SBD (see Section 2). Then, the methodological procedure and a statistical description of the publications found are presented (see Section 3). Next, the state-of-the-art of SBD models and frameworks are discussed (see Section 4). Based on that, a content analysis was performed along with the presentation of the main knowledge gaps and contributions found in the literature and recommendation for future works (see Section 5). Furthermore, the conclusions resulting from this work are provided (see Section 6).

2 Set-based design

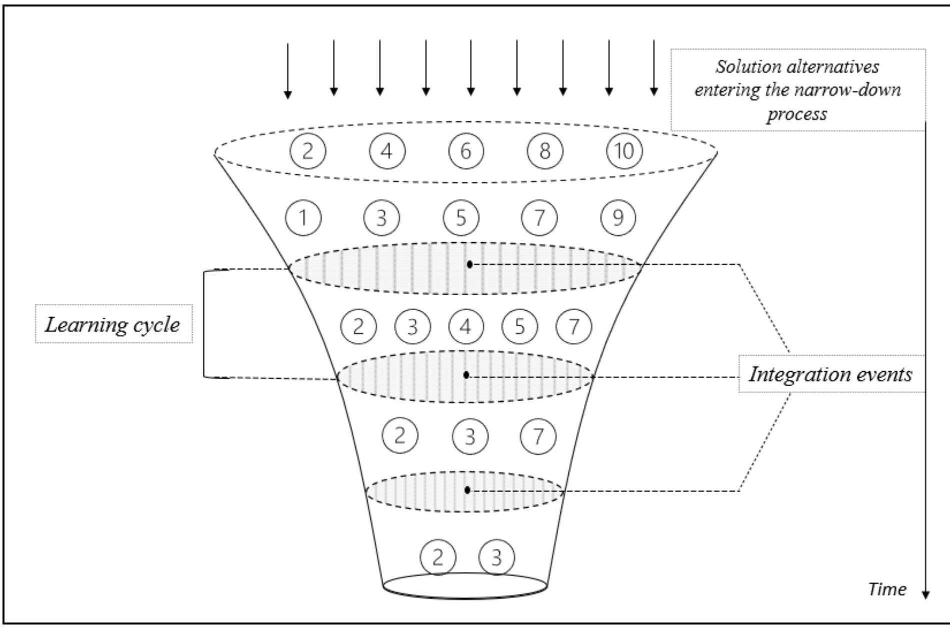
There are two strategies in the product development process to find the concept among the possible solutions for the project, which will result in the final product. The first is to select the best from all possibilities. This strategy is called Point-Based Design (PBD). The second is to phase out alternatives that are proven unfeasible or less attractive until only one final solution remains. This strategy is known as SBD (Morgan and Liker, 2006). Many problems arise from PBD as a consequence of early decision-making and its goal-setting nature. Decisions tend to be made based on ‘desirable things’ due to the lack of knowledge in the initial development phases. As a result, it leads to rework, correction loops, and a tendency to avoid risky projects and innovative solutions, which inhibits innovation, among other issues (Inoue et al., 2013; Majerus, 2016; Pessoa et al., 2007).

SBD, also known as Set-Based Concurrent Engineering (SBCE), is the solution convergence strategy used in Lean Product Development (LPD). It works by developing sets of solutions simultaneously and narrowing them down as they do not meet development goals, whether because they are infeasible, proven inferior, or incompatible among subsystems. SBD may seem inefficient due to its use of resources; nevertheless, it is four times more productive than the PBD strategy (Morgan and Liker, 2006). Considering several solution possibilities for the design problem is an advantage of SBD. Thus, the chances of finding a suitable solution are higher, making SBD superior concerning development risks reduction and knowledge creation (Pessoa et al., 2007).

SBD is known as the most challenging element to adopt in LPD due to the cultural change it demands, for it is not compatible with traditional management methods (Morgan and Liker, 2006). The organisation must develop a strong culture of problem-solving imprinted in the behaviour of the developers (Pessoa and Trabasso, 2017). Furthermore, some elements of LPD must exist for SBD to occur, such as the role of the chief engineer (leader or team that guides and integrates all development), value deployment, responsibility-based management, integration events, learning cycles and knowledge creation focus.

SBD is centred on the process of narrowing down the design space, which occurs as knowledge is gained in each experiment carried out by subsystems. This knowledge is shared in the integration events, which are meetings to discuss the design space considering the knowledge acquired thus far. Based on this, regions can be discarded consistently across the design spaces of all subsystems. As an output, everyone has new knowledge goals to acquire and take to the next event. This period between integration events is called learning cycle. The flow of learning cycles and integrating events is the core of the SBD (see Figure 1). Three principles govern the strategy: map the design space, integrate by intersection, and establish viability before committing (Sobek II et al., 1999).

Figure 1 Set-based design



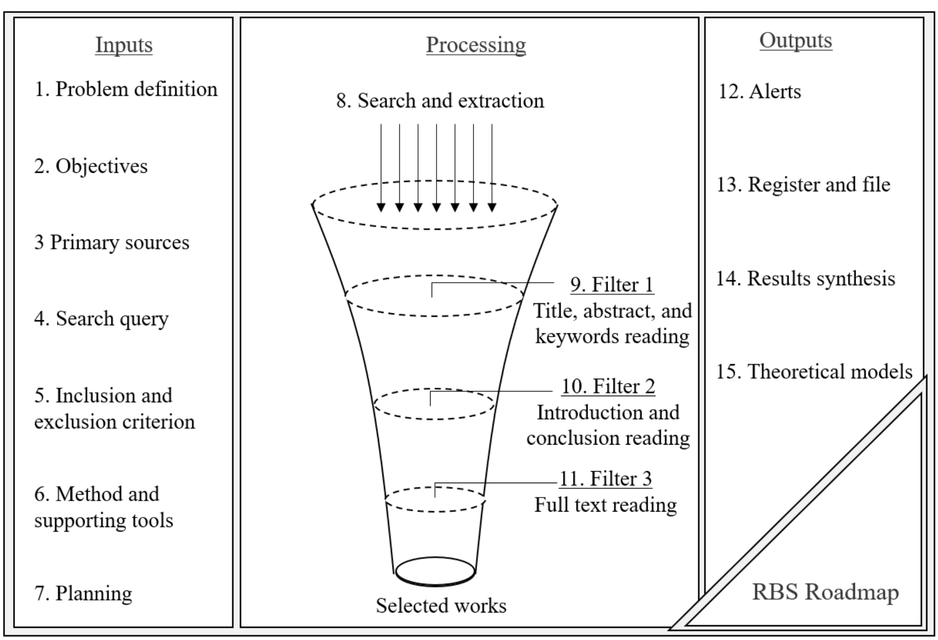
The design space can be defined as the space that contains all possible values for the system or subsystem parameters (Morgan and Liker, 2006). The first principle of SBD, also known as the exploration principle, consists of exploring and mapping the design space through the definition of sets of alternatives to feed the Narrowing Down Process (NDP) (Kerga et al., 2013, 2014; Sobek II et al., 1999). Mapping the design space means defining the feasibility regions, where it is possible to design to meet requirements. Three elements underpin this principle, namely the definition of feasibility regions, the exploration of trade-offs through the design of multiple alternatives and the communication of sets (Sobek II et al., 1999).

The second principle of SBD rules one of the most important criteria for solution alternatives elimination. The logic behind this principle is that there is no point in considering a solution incompatible among subsystems. Therefore, the acceptable design solution must be at the intersection of all design spaces of all parts of the product. This principle is also known as the compatibility principle because it focuses on system compatibility before finishing individual projects (Morgan and Liker, 2006). Three elements constitute this principle: seek the intersection of viable sets, impose minimum constraints, and seek conceptual robustness (Sobek II et al., 1999). The third and last principle is related to gradually narrowing down the alternatives rather than choosing one. The elements associated with this principle are to narrow down the sets of alternatives while increasing the level of detail, remain within the design space once committed and control development by managing the uncertainties in the gates of the development process (Sobek II et al., 1999).

3 Methodological procedures

The SBR was performed following the RBS Roadmap methodology (Conforto et al., 2011), developed for state-of-the-art mapping in the operations management field (see Figure 2). Initially, the research problem and the general objective for the SBR are defined. Regarding this review, the research problem was the following question: 'What are the models and frameworks for the SBD existing in the literature?'. The objective was to identify all works that pertain to this field of study. The next step is to define the primary sources of investigation, through initial exploratory research in web search engines. It indicates which databases are suitable for extraction to compose the pool of works: Scopus®, Engineering Village (Compendex® from Elsevier), Emerald®, Web of Science (Thomson Reuters) and Proquest (ABI Inform). The initial exploratory research also enabled the definition of keywords that would compose the search query.

Figure 2 Research methodology



As the SBD is part of the LPD, works whose subject is LPD may contain models and frameworks to enable SBD. Thus, it was necessary to compose the query with keywords regarding the LPD. Therefore, the query was defined as: ((‘Set Based Concurrent engineering’) OR (‘SBCE’) OR (‘Set Based’) OR (‘SBD’) OR (‘Integrate Product Team’) OR (‘IPT’) OR (‘Lean Product Development’) OR (‘Lean Development’) OR (‘Lean Product Design’) OR (‘Lean Design’) OR (‘Lean Product Engineering’) OR (‘Lean Engineering’)). Once the objectives of the SBR, the query and the sources for the data extraction were defined, the next steps were taken. The publications inclusion criteria considered original articles, reviews, book chapters, dissertations or theses containing the keywords selected in the query in the title, abstract, or keywords. Furthermore, only documents with provided full-text access were considered. All works not meeting these inclusion criteria were excluded during the review process.

Once the data were extracted, they were transferred to a bibliographic manager to filter and organise the results. Next, following the RBS Roadmap, the works were put together in a spreadsheet following a template of relevant fields/columns consisting of authors, year of publication, source, type of document, title, classification (before, after or during the NDP) and highlights of the model/framework. The database extraction resulted in 13,012 publications (see Table 2). After the filtering process, 121 works remained, comprising all SBD models and frameworks in the literature. They were classified by assessing their content using the previously mentioned spreadsheet. Based on an extensive analysis of each model and framework, the main gaps or unsolved questions related to SBD were identified. Also, the main contributions were recognised and presented, along with recommendations for future works.

Table 2 Systematic bibliographic review filtering process

Step	*Filter*	*Pool of publications*
0	Database extraction	13,012
1st	Eliminate duplicates	8538
2nd	Title, abstract and keywords reading	694
3rd	Introduction and conclusion reading	341
4th	Full-text reading	121

3.1 Statistical description

Two important years can be identified by observing the temporal distribution of the 121 models and frameworks published for the SBD. The first is the year 1992 when Lin (1992) presented the first model regarding the representation of sets. Nevertheless, only after 2010 the topic was widely addressed in the literature (see Figure 3). Most models were published in journals and conference proceedings, with the largest number of publications occurring in 2019 and 2020. The publications are reported in 35 different scientific journals and 31 different proceedings of international conferences, not discriminating by conference year. Among these, we highlight the leading publishers: the journal ‘*Concurrent Engineering: Research and Applications*’ and the ‘*International Conference on Engineering Design’ (ICED)* (see Table 3).

Figure 3 Distribution of works

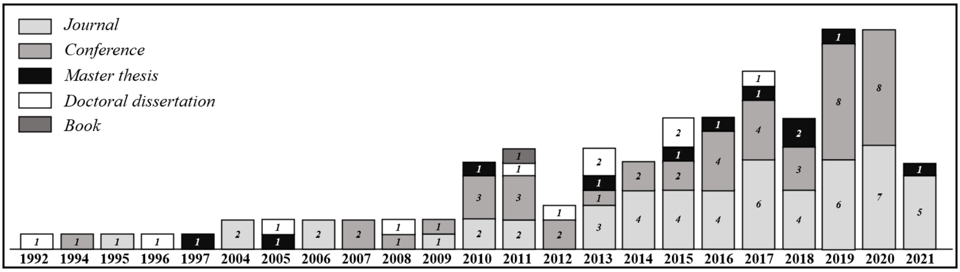


Table 3 Journals and conferences with most publications

Type	*Title*	*Works*
International Journals	*Concurrent Engineering: Research and Applications*	9
	Systems Engineering	5
	Procedia CIRP	3
	Journal of Cleaner Production	2
	International Journal of Advances in Manufacturing Technology	2
	Naval Engineers Journal	2
Conferences Proceedings	*International Conference on Engineering Design (ICED)*	4
	International Design Conference (DESIGN)	3
	International Conference on Concurrent Engineering	2
	IEEE Electric Ship Technologies Symposium	2
	IEEE International Conference on Industrial Engineering and Engineering Management	2
	Annual IEEE International Systems Conference (SYSCON)	2
	Industrial Engineering Research Conference	2

Following an intuitive grouping of works by related themes, i.e., defining the central theme of each work based on its objective and grouping them accordingly, the main themes addressed by the authors were identified (see Table 4) and a proportion of the themes is provided (see Figure 4). The use of trade-off curves, multiscale design and design space representation, managerial models prescribing steps related to the SBD, and models for specific environments were the most approached by the authors. Among the latter, platform designs and complex systems, such as mechatronic systems can be highlighted. Furthermore, a growing interest in SBD was perceived in different research areas and applications. An analysis of the keywords selected by the authors to indicate their subject of study was performed (see Table 5). Most of them were related to the words ‘set-based’, ‘design’, ‘product’ and ‘lean’.

Table 4 Themes approached by the publications

Themes	*Works*
Trade-off curves, multiscale design and design space representation	Araci et al. (2015, 2016a, 2016b, 2017, 2020, 2021); Gray (2011); Hernandez-Luna and Wood (1994); Hernandez-Luna et al. (2010); Inoue and Ishikawa (2009); Inoue et al. (2013); Lin (1992); Madhavan et al. (2008); Mohsin et al. (2020); Nahm and Ishikawa (2005); Ortiz (2021); Parker et al. (2017); Rosen (2015); Sasaki and Ishikawa (2015)
Models for planning activities and processes	Chen et al. (2020); Diels et al. (2015); Kerga et al. (2012a, 2012b); Lu et al. (2020); Martínez (2010); Pessoa et al. (2007); Schuh et al. (2016); Zhong and Dockweiler (2020)
Selection, analysis of alternatives, and uncertainty	Avigad and Moshaiov (2009); Blindheim et al. (2020); Buchanan et al. (2019); Kim (2015); Malak (2008); Pillai et al. (2020a, 2020b); Stolt et al. (2017); Wasim (2012); Wasim et al. (2013)
General models for SBD	Ammar et al. (2019a); Bernstein (1998); Chan (2016); Frye (2010); Georgiades et al. (2019); Kerga et al. (2013, 2014); Khan et al. (2011); Mascitelli (2011); Maulana et al. (2017); Mckenney et al. (2011); Mckenney (2013); Mcnabb et al. (2019); Mebane et al. (2011); Nahm and Ishikawa (2006); Oppenheim (2004); Rempling et al. (2019); Shallcross et al. (2019, 2020b, 2021a); Strom et al. (2016a, 2016b); Wade (2018); Ward et al. (1995)
Early-stage-focused models	Al-Ashaab et al. (2013); Amine et al. (2017); Bertoni and Bertoni (2019); Kennedy et al. (2014); Parnell et al. (2019); Santos et al. (2020); Schäfer and Sorensen (2010); Schulze (2016); Small (2018); Specking et al. (2018); Toshon et al. (2017)
Models for specific environments	Amine et al. (2016, 2017); Ammar et al. (2017, 2018, 2019b, 2019c); Borchani et al. (2018); Borchani et al. (2019); Johanesson et al. (2017); Lee (1996); Landahl et al. (2020); Levandowski et al. (2014a, 2014b); Müller et al. (2019); Raudberget et al. (2014); Raudberget (2015); Raudberget et al. (2015)
SBD transformation	Autzen (2013); Raudberget (2011)
Knowledge and reasoning models	Furian et al. (2011); Maksimovic (2013); Raudberget (2010a, 2010b); Suwanda et al. (2020); Whitcomb and Hernandez (2019)
SBD and different techniques	Bhushan (2007); Essamlali et al. (2017); Fernández (2005); Ishikawa and Sasaki (2020); Kao (2006); Lermen et al. (2018); Saad et al. (2019); Souza and Borsato (2015)
Computer tools to support SBD	Dafflon et al. (2016); Dobrovolskyte (2015); Fitzgerald and Ross (2019); Jonkers and Shahroudi (2020); Qureshi et al. (2014); Rapp et al. (2018); Rapp et al. (2020); Shallcross et al. (2021b, 2021c); Stumpf et al. (2020); Terry (2005); Toche (2017)

Figure 4 Proportion of the themes addressed in the literature

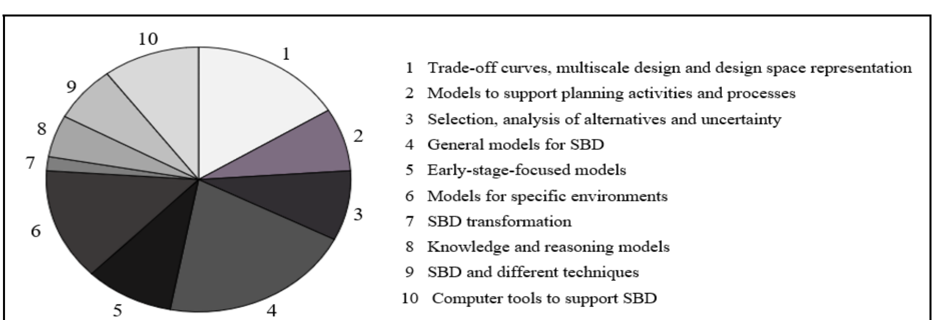


Table 5 Words that appear the most among the keywords

Words	*Number of appearances*
Set based	77
Design	54
Product	34
Lean	33
System	23
Knowledge	20
Contradiction or trade-off	18
Modelling	13
Decision	8
Trade-space or design space	7

4 State-of-the-art in models and frameworks for set-based design

The models approach specific stages of development. No model was found describing the inputs and outputs of the SBD and the NDP simultaneously. Thus, knowledge is dispersed and focused on parts of SBD. Most models are methods and techniques for early development stages, although few present it with the NDP, which plays a central role in SBD. Very little is addressed regarding the SBD management process. Furthermore, LPD enablers for SBD as the integration events and learning cycles are not widely approached. Some models propose an agenda to be followed in these events, yet how they are orchestrated to enable the NDP remains a question. Most models are quantitative, computational and engineering design-oriented. Computational tools are most applied to map and analyse the design space and deal with the complexity and the massive amount of data generated during development. Efforts to gather SBD with other consolidated techniques and principles are consistently made over the years. Among them, one can highlight the adoption of TRIZ (Bhushan, 2007), sustainability (Lermen et al., 2018), agile (Saad et al., 2019), scrum (Fernández, 2005) and Product Lifecycle Management (PLM) (Essamlali et al., 2017).

It was adopted a processual view of SBD, with inputs, transformation process and outputs for the analysis of the literature. Following this logic, the design space is transformed during the SBD, from a space to a point (final solution). There will be inputs to enable this transformation, such as value definition and deployment, planning processes and allocating teams and so on, here called ‘inputs for the narrowing-down process’. The transformation process will be the NDP, by which a region of the design space will become a point as the development advances. Finally, the outputs of the transformation process will be the outcomes of the NDP and the subsequent activities necessary to obtain the product as final adjustments, and so on. The processual view and the steps and activities found in the literature are presented in Figure 5. From the 121 models found, 82 approach inputs for the NDP (see Table 6) and 97 present supporting tools, processes and steps for narrowing down alternatives (see Table 7).

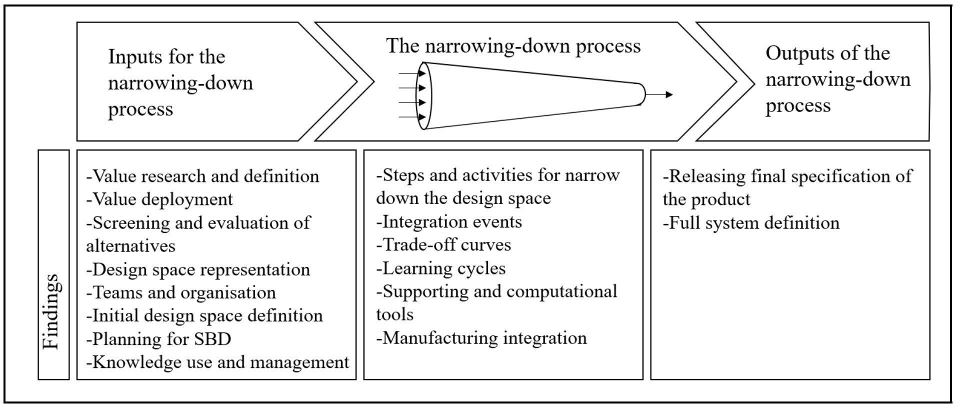
Table 6 Inputs for the set-based design

Steps and tools	*Authors*
Value research and definition	Al-Ashaab et al. (2013); Ammar et al. (2017, 2019a, 2019b, 2019c); Araci et al. (2017); Autzen (2013); Bhushan (2007); Borchani et al. (2019); De Oliveira (2017); De Oliveira et al. (2017, 2018); Dobrovolskyte (2015); Johanesson et al. (2017); Kennedy et al. (2014); Kerga et al. (2013, 2014); Khan et al. (2011); Landahl et al. (2020); Lermen et al. (2018); Mascitelli (2011); Maulana et al. (2017); Mebane et al. (2011); Müller et al. (2019); Parnell et al. (2019); Raudberget et al. (2015); Raudberget (2015); Santos et al. (2020); Schuh et al. (2016); Siiskonen (2019); Small (2018); Specking et al. (2018); Ström et al. (2016a, 2016b); Toche (2017)
Value deployment	Ammar et al. (2017, 2019a, 2019b, 2019c); Autzen (2013); Bhushan (2007); Borchani et al. (2019); De Oliveira (2017); De Oliveira et al. (2017, 2018); Dobrovolskyte (2015); Fernández (2005); Johanesson et al. (2017); Kao (2006); Kerga et al. (2012a, 2012b, 2013; 2014); Khan et al. (2011); Landahl et al. (2020); Lermen et al. (2018); Levandowski et al. (2014a, 2014b); Madhavan et al. (2008); Mascitelli (2011); Mebane et al. (2011); Müller et al. (2019); Raudberget et al. (2014, 2015); Raudberget (2015); Schuh et al. (2016); Siiskonen (2019)
Screening and evaluation of alternatives	Al-Ashaab et al. (2013); Amine et al. (2017); Autzen (2013); Avigad and Moshaiov (2009); Bertoni and Bertoni (2019); Chan (2016); Dobrovolskyte (2015); Essamlali et al. (2017); Fernández (2005); Lee (1996); Maulana et al. (2017); Müller et al. (2019); Parker et al. (2017); Raudberget (2011); Schäfer and Sorensen (2010); Schuh et al. (2016); Schulze (2016); Toche (2017)
Design space representation	Fernández (2005); Gray (2011); Hernández-Luna and Wood (1994); Hernández-Luna et al. (2010); Inoue and Ishikawa (2009); Ishikawa and Sasaki (2020); Lee (1996); Lin (1992); McKenney (2013); Nahm and Ishikawa (2005); Nahm and Ishikawa (2006); Ortiz (2021); Pillai et al. (2020a, 2020b); Rosen (2015); Sasaki and Ishikawa (2015); Toche (2017)
Teams and organisation	Al-Ashaab et al. (2013); Chen et al. (2020); Dobrovolskyte (2015); Frye (2010); Khan et al. (2011); Lermen et al. (2018); Lu et al. (2020); Mckenney et al. (2011); Schulze (2016)
Initial design space definition	Al-Ashaab et al. (2013); Araci et al. (2017); Avigad and Moshaiov (2009); Bhushan (2007); Fernández (2005); Frye (2010); Khan et al. (2011); Lee (1996); Lermen et al. (2018); Lin (1992); Mckenney et al. (2011); Parker et al. (2017); Toshon et al. (2017)
Planning for SBD	Autzen (2013); Chen et al. (2020); De Oliveira (2017); De Oliveira et al. (2017, 2018); Diels et al. (2015); Dobrovolskyte (2015); Essamlali et al. (2017); Frye (2010); Kerga et al. (2013, 2014); Khan et al. (2011); Lermen et al. (2018); Maksimovic (2013); Martínez (2010); Mascitelli (2011); Maulana et al. (2017); Mebane et al. (2011); Pessôa et al. (2007)
Knowledge use and management	Araci et al. (2020); Dobrovolskyte (2015); Essamlali et al. (2017); Furian et al. (2011); Suwanda et al. (2020); Zhong and Dockweiler (2020)

Table 7 The narrowing down process

Steps and tools	*Authors*
Steps and activities for narrow down the design space	Al-Ashaab et al. (2013); Amine et al. (2016, 2017); Ammar et al. (2017, 2018, 2019a, 2019b, 2019c); Araci et al. (2015, 2016a, 2016b, 2017); Autzen (2013); Bernstein (1998); Bhushan (2007); Borchani et al. (2018); Borchani et al. (2019); Buchanan et al. (2019); Chan (2016); Chen et al. (2020); Dafflon et al. (2016); De Oliveira et al. (2017, 2018); Dobrovolskyte (2015); Fernández (2005); Frye (2010); Georgiades et al. (2019); Gray (2011); Hernández-Luna et al. (2010); Inoue and Ishikawa (2009); Inoue et al. (2013); Johanesson et al. (2017); Kao (2006); Kerga et al. (2012a, 2012b); Khan et al. (2011); Kennedy et al. (2014); Landahl et al. (2020); Lee (1996); Levandowski et al. (2014a, 2014b); Madhavan et al. (2008); Maulana et al. (2017); Mckenney et al. (2011); McKenney (2013); Mebane et al. (2011); Mohsin et al. (2020); Müller et al. (2019); Nahm and Ishikawa (2005); Nahm and Ishikawa (2006); Oppenheim (2004); Parker et al. (2017); Parnell et al. (2019); Rapp et al. (2018); Rapp et al. (2020); Raudberget (2010a, 2010b, 2011); Raudberget et al. (2015); Raudberget (2015); Rempling et al. (2019); Rosen (2015); Saad et al. (2019); Sasaki and Ishikawa (2015); Shallcross et al. (2019, 2020b, 2021a); Siiskonen (2019); Small (2018); Souza and Borsato (2015); Specking et al. (2018); Ström et al. (2016a, 2016b); Toche (2017); Toshon et al. (2017); Wade (2018); Ward et al. (1995); Whitcomb and Hernandez (2019)
Integration events	De Oliveira (2017); Mascitelli (2011); Zhong and Dockweiler (2020)
Trade-off curves	Ammar et al. (2018, 2019a); Araci et al. (2016a, 2016b, 2017, 2020); Kao (2006); Khan et al. (2011); Kerga et al. (2013, 2014); Mohsin et al. (2020); Parnell et al. (2019); Small (2018); Specking et al. (2018)
Learning cycles	Araci et al. (2015); De Oliveira (2017); De Oliveira et al. (2017, 2018); Mascitelli (2011); Zhong and Dockweiler (2020)
Supporting and computational tools	Amine et al. (2016); Bhushan (2007); Borchani et al. (2018); Dafflon et al. (2016); Fernández (2005); Fitzgerald and Ross (2019); Frye (2010); Furian et al. (2011); Georgiades et al. (2019); Gray (2011); Hernández-Luna and Wood (1994); Inoue and Ishikawa (2009); Inoue et al. (2013); Malak (2008); Mascitelli (2011); McNabb et al. (2019); Nahm and Ishikawa (2005); Qureshi et al. (2014); Rapp et al. (2018, 2020); Raudberget (2011); Rosen (2015); Sasaki and Ishikawa (2015); Terry (2005); Toche (2017); Toshon et al. (2017); Wasim (2012); Wasim et al. (2013)
Manufacturing integration	Ammar et al. (2018); Borchani et al. (2019); Kerga et al. (2012b); Kim (2015); Landahl et al. (2020); Lermen et al. (2018); Levandowski et al. (2014b); Siiskonen (2019); Stolt et al. (2017); Wasim (2012); Wasim et al. (2013)

Figure 5 Inputs for the set-based design



4.1 Inputs for the narrowing down process

The most mentioned activities enabling the NDP to occur are value definition and deployment, planning and design space representation, mapping and screening. QFD, Value Function Deployment (VFD) and functional flow diagrams are tools cited by the authors to support the execution of these activities. Furthermore, they can assist in identifying subsystems and functions, their relations and planning for manufacturing (Al-Ashaab et al., 2013; De Oliveira, 2017; De Oliveira et al., 2017; Essamlali et al., 2017; Kao, 2006; Kerga et al., 2014; Lermen et al., 2018; Toshon et al., 2017). The VFD is an adaptation of the QFD, presented by Pessoa and Trabasso (2017), composed of two interconnected matrices, to identify and prioritise the correlation between all the value items expected for the project and to perform the value deployment to the value delivery functions.

Establishing initial value ranges for key parameters, assessing products from competitors and identifying and prioritising systems contradictions are also mentioned as early-stage activities (De Oliveira, 2017; De Oliveira et al., 2017; Kerga et al., 2013, 2014; Mebane et al., 2011; Parker et al., 2017; Schäfer and Sorensen, 2010). The adoption of the SBD can be inhibited by the massive use of resources needed to carry out the NDP. Thus, some strategies have been proposed to balance the design space and the resources available for the development. One is to define the desired level of innovation for each part of the product. Consequently, only the most innovative parts will be narrowed down while the others can be chosen to fit the final solution, according to a PBD strategy (Al-Ashaab et al., 2013; Ammar et al., 2018; Autzen, 2013; Khan et al., 2011; Maulana et al., 2017; Pessoa and Trabasso, 2017). A method proposed to support this decision is the convergence-uncertainty-portfolio (Schuh et al., 2016). Another approach is to calculate the maturity of the sets to discard those that are least interesting and focus resources on those with more probability of success (Shallcross et al., 2020b, 2021a).

Still regarding to balancing resources, many models were proposed to support the screening of concepts in SBD, i.e., by removing areas of the design space that have least probability of success early in the development (Al-Ashaab et al., 2013; Amine et al., 2017; Autzen, 2013; Avigad and Moshaiov, 2009; Bertoni and Bertoni, 2019; Chan, 2016; Dobrovolskyte, 2015; Essamlali et al., 2017; Fernández, 2005; Lee, 1996; Maulana et al., 2017; Müller et al., 2019; Parker et al., 2017; Raudberget, 2011; Schäfer and Sorensen, 2010; Schuh et al., 2016; Schulze, 2016; Toche, 2017). This activity can be assisted by decision matrixes, metrics based on requirements and expected performance, Technology Readiness Level (TRL) analysis and evaluation against uncertainty (Al-Ashaab et al., 2013; Amine et al., 2016; Mascitelli, 2011; Schuh et al., 2016). To that end, one can rely on previous projects and knowledge and competing products as sources of information (Al-Ashaab et al., 2013; Bhushan, 2007; Furian et al., 2011; Khan et al., 2011; Maksimovic, 2013; Schäfer and Sorensen, 2010).

The first methods for SBD found in literature approached parameter design to search for feasibility areas in the design space (Hernandez-Luna and Wood, 1994; Lin, 1992). After that, Hernandez-Luna et al. (2010); Inoue and Ishikawa (2009); Inoue et al. (2013); Nahm and Ishikawa (2005, 2006); Raudberget (2011); Rosen (2015); Sasaki and Ishikawa (2015) and Toche (2017) proposed methods for the design space representation. Efforts were made not only to communicate the current design space but also to inform where the preferable solutions are (Hernandez-Luna and Wood, 1994; Inoue et al., 2013; Ishikawa and Sasaki, 2020; Mckenney et al., 2011; Nahm and Ishikawa, 2005, 2006; Sasaki and Ishikawa, 2015). Among the methods related to the set representation are the 'preference set-based design' (Inoue and Ishikawa, 2009; Inoue et al., 2013; Nahm and Ishikawa, 2005; Sasaki and Ishikawa, 2015), the extended morphological matrix (Raudberget, 2011), uncertainty modelling (Gray, 2011) and the multi-domain views in engineering design (Rosen, 2015; Toche, 2017). Furthermore, a multi-scale process-structure-property relationship was presented to support the design process (Rosen, 2015).

The Enhanced Function-Means (E-FM) modelling was proposed to represent sets to support the visualisation of relations in technological and physical domains and to enable the use of the Configurable Components (CC) in the design of platform products (Ammar et al., 2017; Johanesson et al., 2017; Levandowski et al., 2014a, 2014b; Raudberget et al., 2014; Raudberget, 2015; Raudberget et al., 2015; Toche, 2017). Furthermore, methods that connect E-FM to geometric features (Müller et al., 2019) and production systems analysis to support changing the bandwidth of platforms were developed (Landahl et al., 2020; Levandowski et al., 2014b).

Some works approached planning and coordinating activities in SBD (Autzen, 2013; De Oliveira, 2017; Diels et al., 2015; Frye, 2010; Lermen et al., 2018; Martínez, 2010; Mascitelli, 2011; Pessoa et al., 2007; Schulze, 2016). Among the tools proposed to support such activities is the deliverable roadmap, based on responsibility-based management (De Oliveira, 2017; Mascitelli, 2011). The concept of gates with SBD is also addressed by connecting development phases with quality gates (Autzen, 2013; Souza and Borsato, 2015). Furthermore, efforts were made to integrate manufacturing evaluation in the NDP (Ammar et al., 2018; Borchani et al., 2019; Kerga et al., 2012b; Kim, 2015; Landahl et al., 2020; Lermen et al., 2018; Levandowski et al., 2014b; Stolt et al., 2017; Wasim, 2012; Wasim et al., 2013), as a cost modelling system with poka-yoke rules for design alternatives (Wasim, 2012; Wasim et al., 2013) and a filtering technique focused on manufacturing resources (Kim, 2015).

Computational tools and methods to support SBD were proposed in Amine et al. (2016); Bhushan (2007); Borchani et al. (2018); Dafflon et al. (2016); Fernández (2005); Fitzgerald and Ross (2019); Frye (2010); Furian et al. (2011); Georgiades et al. (2019); Gray (2011); Jonkers and Shahroudi (2020); Malak (2008); Mascitelli (2011);

Mcnabb et al. (2019); Qureshi et al. (2014); Rapp et al. (2018, 2020); Raudberget (2011); Rosen (2015); Sasaki and Ishikawa (2015); Stumpf et al. (2020); Terry (2005); Toche (2017); Toshon et al. (2017); Wasim (2012); Wasim et al. (2013), as the modelling of partially-defined system alternatives to support decision making (Malak, 2008) and the use of artificial intelligence for processing the massive volume of data generated by exploration of design space (Fitzgerald and Ross, 2019). Computer tools used in development activities to manipulate images are PBD oriented because they enable only the visualisation of one single design alternative at a time. To solve this problem a set-based interface was developed to compare more than one solution simultaneously (Terry, 2005).

Regarding quantitative, computational, and/or engineering models, major works focus on screening concepts and techniques for filtering and communicating the design space during the NDP. The most applied techniques for developing quantitative models for SBD are fuzzy arithmetic, interval and propagation theorems and arithmetic, and Multi-Objective Optimisation (MOO). Regarding the identification and prioritisation of contradictions, the analysis of the roof of QFD matrixes (Kerga et al., 2014; De Oliveira, 2017; De Oliveira et al., 2018) and contradictions classification (Kerga et al., 2014) were suggested. The trade-off curves are cited by many authors (Ammar et al., 2018; Araci et al., 2015, 2016a, 2016b, 2017, 2020, 2021; Maksimovic, 2013; Maulana et al., 2017; Mohsin et al., 2020), and models were proposed for its generation (Araci et al., 2015, 2016a, 2016b, 2017, 2020, 2021).

4.2 The narrowing down process of set-based design

Some authors consider the NDP from a sequential perspective, in which the activities are prescribed in a sequence with inputs and outputs (Araci et al., 2016a, 2016b, 2017, 2020, 2021; Essamlali et al., 2017; Lermen et al., 2018). De Oliveira (2017); Mascitelli (2011) and Oppenheim (2004) considered the NDP through a flow perspective, evidencing integration events and learning cycles. Furthermore, a cyclic perspective was found (Parker et al., 2017). Four exclusion criteria are cited in the literature: when an option does not meet the desired requirements, is proven unfeasible, is incompatible with the other options from other subsystems and is deemed inferior to another option in every attribute (Autzen, 2013; Frye, 2010; Mebane et al., 2011; Raudberget, 2010a, 2010b, 2011).

The trade-off curves are cited as one of the main tools that support communication and narrowing (Araci et al., 2015, 2016a, 2016b, 2017, 2020, 2021; Maksimovic, 2013; Maulana et al., 2017; Mohsin et al., 2020) along with the obeya room and visual boards (Zhong and Dockweiler, 2020). Techniques for identification of the trade-offs involved in the project by analysing the roof of QFD matrixes (Kerga et al., 2014; De Oliveira, 2017; De Oliveira et al., 2018) and contradictions classification (Kerga et al., 2014) were suggested. Furthermore, models for trade-off curves drawing and their use in filtering concepts were proposed (Araci et al., 2015, 2016a, 2016b, 2017, 2020, 2021).

Some approaches suggest that first the exclusion of alternatives should be made by requirements and feasibility, then by compatibility and after that, a final reduction method is required (Ammar et al., 2018; Frye, 2010). Other approaches propose that first, the project requirements should be connected to system decisions, then trade-offs compared to configurations and detailed decisions and finally, trade-offs and limit curves are analysed (Kennedy et al., 2014). The comparison between the cost and value of alternatives to verify which ones are dominant was suggested as a discarding method (Wade, 2018). Furthermore, efforts were made to demonstrate how the level of abstraction of the product changes as the knowledge level increases (Saad et al., 2019).

Methods to 'integrate by intersection' were proposed (Mckenney, 2013; Nahm and Ishikawa, 2005; Toche, 2017). Furthermore, virtual prototyping, factory simulation and the interconnectivity with physical prototyping are mentioned to overlap design spaces (Toche, 2017). Nevertheless, few advances in this field were made since none of the models provide in-depth approaches to this issue and demonstrate how this is performed in an NDP context with integration events. Integration events are approached by few works (Mascitelli, 2011; Oppenheim, 2004; Zhong and Dockweiler, 2020) in the same way as learning cycles (De Oliveira, 2017; Mascitelli, 2011; Oppenheim, 2004).

Learning-cycle events and design review and freeze events occur during the NDP (Mascitelli, 2011). An approach was proposed using the Toyota Kata to manage the NDP, learning cycles and integration events (De Oliveira et al., 2018). Furthermore, efforts were made to present methods to control the convergence of design space (Bernstein, 1998; Mckenney et al., 2011; Mebane et al., 2011). When a subsystem converges early in the process or has an insignificant parameter range, its removal from the NDP is recommended (Frye, 2010). In this case, the best design choice should be made to fit the system set, according to the PBD strategy (Autzen, 2013; Khan et al., 2011).

A model to support decision-making based on reactive multi-agent systems was developed (Dafflon et al., 2016). Among the activities presented in the literature to perform the narrowing down of alternatives, the most mentioned are the exploration of sets through simulation, analysis, experiments, trade-off curves, prototypes and tests, and finding intersections between design spaces reducing it by eliminating incompatible and unfeasible solutions (Ammar et al., 2019a, 2019b, 2019c; Araci et al., 2016a, 2016b, 2017, 2020; Autzen, 2013; Bernstein, 1998; Essamlali et al., 2017; Frye, 2010; Khan et al., 2011; Mascitelli, 2011; Maulana et al., 2017; Mckenney et al., 2011; Mebane et al., 2011; Parker et al., 2017; Parnell et al., 2019; Raudberget, 2010a, 2010b, 2011; Shallcross et al., 2019; Small, 2018; Specking et al., 2018; Ward et al., 1995).

Manufacturing participation during the NDP is a source of information that can bound and narrow the design space (Essamlali et al., 2017; Kao, 2006; Kerga et al., 2012a, 2012b; Khan et al., 2011; Mascitelli, 2011). Attributing the larger possible flexibility for manufacturing and delay specifications is the path to a robust design (Kerga et al., 2012a, 2012b; Toshon et al., 2017). A methodology was proposed to evaluate and plan the manufacturing process for each alternative (Kerga et al., 2012a, 2012b). Autzen (2013) affirmed that the involvement of services and suppliers is rarely mentioned in the literature. Some authors believe that the DF-X can be applied during the NDP (Kao, 2006; Lermen et al., 2018; Mascitelli, 2011), with the support of Computer-Aided Design (CAD) and QFD (Essamlali et al., 2017; Kao, 2006).

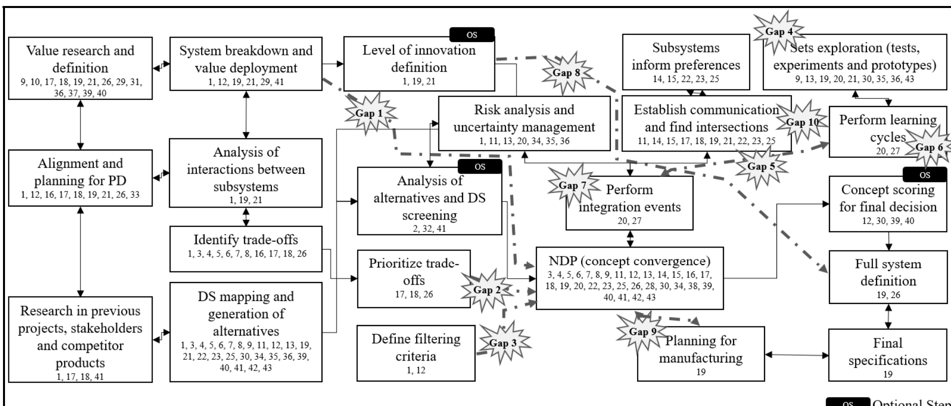
Kennedy et al. (2014) and Mebane et al. (2011) argued that the development after the NDP follows PBD cycles or traditional development approaches. These approaches are usually strongly supported by decision matrixes to choose the best option from those that were previously narrowed down (Frye, 2010; Maulana et al., 2017). Once the final solution is chosen, the detailed design begins (Khan et al., 2011; Lermen et al., 2018), by releasing the final specification of the product, including its tolerances and final parameters (provided by manufacturing), 3P (Production, Preparation, Process), value engineering and, the full system definition (Khan et al., 2011; Lermen et al., 2018).

5 Gaps and opportunities identified in the literature

Among the results of the SBR, one can highlight the absence of a work that generally addresses SBD, presenting inputs, outputs and detailing the NDP. The models mainly introduced tools to assist in finding, selecting and representing the design space and the main steps of the SBD. Many efforts were made to present early-stage methods and techniques, and quantitative, computational and engineering design-oriented models. Nevertheless, there is an absence concerning the management of the NDP. Since the knowledge focused on some parts, it may be difficult to find consistent guidelines for a well-established SBD.

An analysis with models that prescribe steps to perform SBD is presented in Figure 6. Models addressing a specific activity integrating the SBD with other techniques or computational tools were not included in the analysis, since the objective is to identify which contributions were made towards a comprehensive process and method. It was observed that there are no conflicting views on SBD. The models, in general, are complementary, looking at the same process from different perspectives and placing emphasis on specific points of the process. Therefore, the knowledge concerning this field of study is divided into several works. It is necessary to provide methods to connect parts of the process and clarify how to perform some steps.

Figure 6 Towards a process for set-based design: overview of managerial models in the literature



[1]Al-Ashaab et al. (2013); [2]Amine et al. (2017); [3]Araci et al. (2015); [4]Araci et al. (2016a); [5]Araci et al. (2016b); [6]Araci et al. (2017); [7]Araci et al. (2020); [8]Araci et al. (2021); [9]Bernstein (1998); [10]Bertoni; Bertoni (2019); [11]Chan (2016); [12]Frye (2010); [13]Georgiades et al. (2019); [14]Inoue and Ishikawa (2009); [15]Inoue et al. (2013); [16]Kennedy et al. (2014); [17]Kerga et al. (2013); [18]Kerga et al. (2014); [19]Khan et al. (2011); [20]Mascitelli (2011); [21]Maulana et al. (2017); [22]Mckenney et al. (2011); [23]Mckenney (2013); [24]Mebane et al. (2011); [25]Nahm and Ishikawa (2006); [26]Oliveira et al. (2017); [27]Oppenheim (2004); [28]Parnell et al. (2019); [29]Pessoa and Trabasso (2017); [30]Rempling et al. (2019); [31]Santos et al. 2020; [32]Schäfer; Sorensen (2010); [33]Schulze (2010); [34]Shallcross et al. (2019); [35]Shallcross et al. (2020b); [36]Shallcross et al. (2021a); [37]Small (2010); [38]Specking et al. (2018); [39]Strom et al. (2016a); [40]Strom et al. (2016b); [41]Toshon (2017); [42]Wade (2018); [43]Ward et al. (1995).

It was identified 10 gaps and 3 optional steps in the literature. Two optional steps are related to compatibility between the design space and the resources available for development and one to the end of the NDP, as shown in Figure 6. In the case of incompatibility between the design space and resources, regions with less probability of success and/or subsystems with low innovation levels should be removed from the NDP. Concerning the end of the NDP, after the filtering process, a single solution or a small set of solutions for each subsystem is obtained. When a small set of alternatives remains, steps and activities are needed to decide which solution is the best.

Even though many works discuss value, little is approached about value deployment, which is the primary function of QFD matrixes. Although QFD is a tool with its roots in lean, except for the model of De Oliveira (2017), no demonstration of its use for value deployment in an LPD environment has been found. The work of De Oliveira (2017) partially filled this gap by demonstrating the use of the second and third levels of deployment for subsystems and components. The QFD has more levels of deployment though, including production planning and planning for process control.

No demonstration was found of how value deployment is used in SBD, especially regarding the NDP (Gap 1, Figure 6). Furthermore, how to use trade-off curves in the context of integration events and learning cycles remains a question (Gap 2, Figure 6). There is no consensus on when to draw and study trade-off curves, either before or during the NDP. Nevertheless, it has already been demonstrated how it is possible to identify design trade-offs (De Oliveira, 2017; De Oliveira et al., 2018; Kerga et al., 2014), how to draw trade-off curves and analyse design concepts with them (Araci et al., 2015, 2016a, 2016b, 2017, 2020, 2021).

Planning activities for SBD is crucial for its success since several subsystems develop the product in parallel. Thus, it demands at least a minimum level of activity coordination, which can only be achieved by planning the flow of information, key decision-making and integration events. Nevertheless, this is not widely approached in literature. One can highlight the works of Mascitelli (2011) and De Oliveira (2017), who proposed the use of responsibility-based management assisted by the deliverable roadmap. Furthermore, the Toyota Kata approach was brought as a solution for learning cycle management (De Oliveira et al., 2018).

Initiatives to balance design space with the resources available are a concern in the literature. Models were proposed for discarding solutions or spare resources as concept screening methods, the definition of the innovation level of each part, the amount and depth of experiments and the maturity of concepts. Nevertheless, there are still opportunities regarding how to plan and manage those constraints. The design space mapping and representation are vastly approached and consolidated in literature. Important advances in the field were made by introducing the possibility of different abstraction levels as proposed by Rosen (2015). This multilevel representation has the potential to enhance design space visualisation, especially when the requirements are associated with structural, mechanical and physical performances. Furthermore, connecting this multilevel representation with integration events and learning cycles could represent a significant advance in SBD.

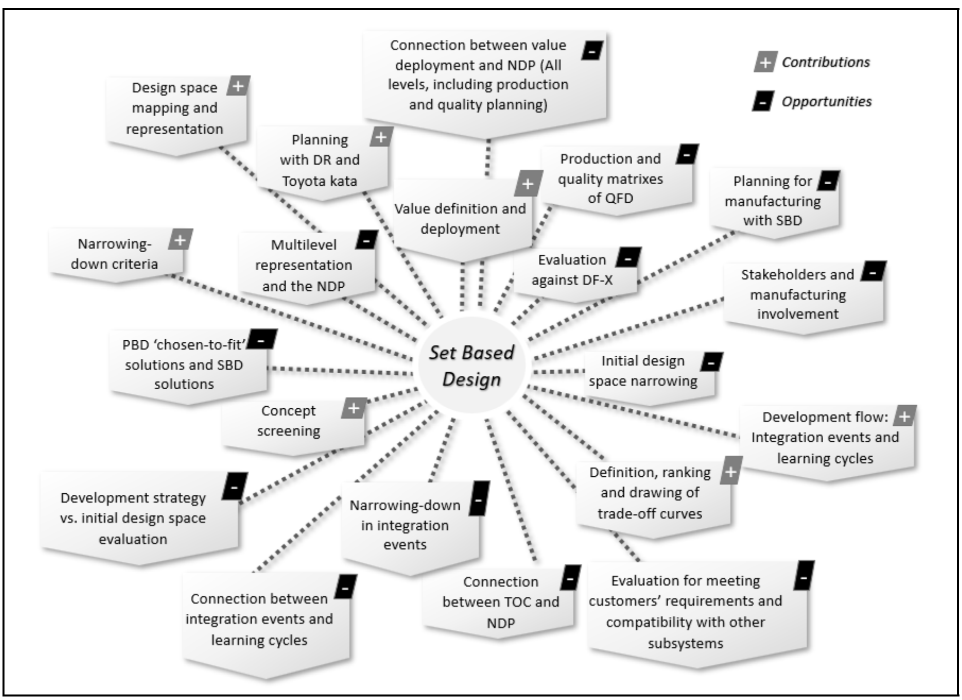
The use of previous knowledge is addressed as important for the NDP, especially in generating alternatives and bounding the design space. Still, how to store and reuse knowledge is not directly mentioned, except for trade-off curves. These issues constitute important gaps in the literature as they are crucial for the SBD. There is a consensus regarding the general criteria adopted to narrow-down solutions, which are meeting the requirements of customers, the feasibility of the solution, compatibility with other subsystems and being proven inferior. Nevertheless, it is not clear in the literature how the sets are evaluated based on these criteria (Gap 3, Figure 6). Furthermore, it is mentioned that they are applied in specific moments of the NPD, though no clarification is given.

Concerning compatibility between subsystems, one can highlight the efforts made by Mckenney (2013) and Nahm and Ishikawa (2005). Nevertheless, further advance is necessary regarding methods to compare design spaces and decide based on the compatibility criteria (Gap 10, Figure 6). Furthermore, how and when this occurs is a remaining question. During the NDP, experimentation to test design space regions will result in trade-off curves, limit curves and relations between variables. Nevertheless, the management and planning of experiments are not approached (Gap 4, Figure 6).

Oppenheim (2004) detailed that learning cycles occur between integration events to answer project questions through experiments and activities. Nevertheless, this is not demonstrated by any author in the found literature. Further development showing in detail learning cycles, integration events and their connection is necessary (Gaps 5, 6, and 7, Figure 6). After de NDP, PBD cycles take place to develop the solution thoroughly. Nevertheless, there will be parts, components or even subsystems planned as chosen-to-fit solutions. It was found no literature that proposed how to develop these parts and how to connect them with the NDP (Gap 8, Figure 6).

The participation of stakeholders and manufacturing is a gap in the literature as few works approached this issue. There is no consensus regarding the moment manufacturing and suppliers should be involved in the NDP (Gap 9, Figure 6). It is important to mention that the application of the production and quality matrixes of QFD and their connection with the SBD is not approached in the literature. Manufacturing participation is a critical aspect of SBD, but it is one of the least addressed by the authors. The main contributions and the gaps found in the literature are presented in Figure 7.

Figure 7 Gaps and contributions found in the literature



5.1 Recommendations for future works

The state-of-the-art analysis presented in the previous section provided the main gaps and opportunities which form a background for further advancing knowledge about SBD. It paves the way for new more detailed, robust and implementation-oriented works, providing the tools for spreading SBD and its benefits. The gaps identified in the literature are mostly related to linking information, steps and activities in SBD environments. It is a consequence of the dispersion of knowledge in the field. Some parts and problems are widely discussed, but it is noticed that the models rarely address more than one part of the SBD. Even if they do not present conflicting views and are complementary, it is necessary to advance towards holistic and comprehensive models that connect and close the development process in SBD environments.

The main recommendation of this research for future works is to demonstrate in detail the product development flow in SBD, connecting learning cycles, integration events and the NDP. Since most efforts are in the early stages of development, it is the most knowledge-advanced SBD part. The use in the NDP of the information gathered at the early stages was not approached in the literature, even though much is emphasised about the importance of defining value for narrowing the design space. An opportunity was identified to connect inputs for the NDP and the process itself, which includes value definition and deployment, planning of learning cycles and integration events, concept screening activities, the definition of development strategy, trade-off curves drawing and design space mapping and representation.

The most critical part of SBD is the NDP, and even so, very little is clarified in the literature. It is necessary to connect the parts to detail the flow of the NDP, i.e., design space representation tools and the preference of designers, integration events, learning cycles, experiments, trade-off curves and development planning. Furthermore, the involvement of stakeholders, manufacturing and supply chain during and after the NDP is few mentioned. Besides, strategies for balancing resources available for development and the design space size are a concern in the literature.

Models were developed to reduce the design space by discarding areas with less probability of success. Nevertheless, few are mentioned strategies regarding the level of innovation of parts or other techniques that can be applied to provide compatibility between resources available and demanded. Not only methods such as concept screening and the definition of the innovation level, but controlling the amount and depth of experiments and the maturity of concepts could be used. For future works, methods and techniques are recommended to plan and manage this compatibility. The gaps and contributions presented in this paper provided a background for future works that can foster SBD implementation:

1 Demonstrate the use of value deployment for narrow-down alternatives in the NDP;

2 Demonstrate the use of trade-off curves during the NDP, not only how to narrow-down concepts but how they are presented and generated in the context of integration events and learning cycles;

3 Approach the evaluation of sets for filtering based on the criteria adopted during integration events;

4 Modelling how to plan experiments considering limited resources to develop and manage the execution during the learning cycles;

5 Demonstrate how learning cycles and integration events are connected and present a method to conduct them in an integrative approach;

6 Present methods for learning cycles and integration events management and execution;

7 Methods to decide on the level of innovation of each part to match resources and design space;

8 Demonstrate how to develop PBD solutions in an integrative manner with SBD;

9 Present the participation of stakeholders and manufacturing in the NDP and how they contribute to design space reduction;

10 Develop techniques to narrow-down solutions based on compatibility criteria in the integration events;

11 A further advance in techniques for balancing design space with the resources available;

12 Model the knowledge capture, management and storage in SBD environments.

6 Conclusions

The studies on SBD showed that among the strategies of solution convergence for product development, it presents better results, lower risks and promotes an enabling environment for innovation. Nevertheless, as many authors affirm, there are important factors associated with integration, learning and organisational culture that are intrinsically correlated with the success of SBD implementation. It was concluded that these factors must considered when developing models and frameworks for SBD.

The method RBS Roadmap was applied. It was proposed by Conforto et al. (2011) for state-of-the-art mapping in the operations management field. The objective was identifying all works that present methods or frameworks for SBD. It was found 121 works reported in 35 scientific journals, 31 proceedings of international conferences, 1 book, 11 master thesis and 11 doctoral dissertations. We concluded that most publications approach the use of trade-off curves, multiscale design and design space representation, managerial models, and models for specific environments as platform products and complex systems. Furthermore, the leading keywords in this field of study are ‘set-based’, ‘design’, ‘product’ and ‘lean’.

Based on an overview of the SBR results, it was concluded that it was not found any work that addresses SBD broadly since none approaches inputs, outputs and the NDP simultaneously. Furthermore, there is a notable focus on explaining the SBD methods and techniques for early stages in the development process and little enlightenment in NDP. It was observed that the research authors consistently agree on the lack of comprehensive models that can support SBD adoption. The use of trade-off curves, manufacturing and supply chain involvement, learning cycles, integration events and narrowing down criteria application is widely mentioned as practical SBD enablers, but they remain scarce in the literature.

It was concluded that the models are specific to certain activities and steps of the SBD, mostly focused on the early stages of development. No conflicting approaches or different views of SBD were found. The models generally complement each other, looking at the same process from different perspectives and placing emphasis on different moments of SBD. Therefore, the knowledge concerning this field of study is divided into several works and it is necessary to connect parts of SBD and clarify how to perform some steps. Regarding the managerial models found in the literature, it was identified three optional steps: the design space screening and the level of innovation definition (in the case of incompatibility between design space and resources available), and the final scoring of solutions at the end of the NDP.

An effort was made to build a process for SBD to demonstrate the contributions of its managerial models and the gaps that may hinder the adoption of this strategy. It was found 10 gaps: (1) The use of value deployment in the NDP; (2) the use of trade-off curves during the NDP along with integration events and learning cycles; (3) evaluation of sets based on filtering criteria in the NDP; (4) Management and planning of experiments and tests (prototyping, failure tests, and so on); (5) Connection between learning cycles and integration events; (6) Learning cycles management and execution; (7) Integration events management and execution; (8) development of chosen-to-fit solutions (PBD solutions); (9) Participation of stakeholders and manufacturing in the NDP; (10) Techniques to narrow-down solutions based on compatibility criteria.

In addition to the aforementioned gaps, some efforts were identified to balance design space with the resources available. Methods such as concept screening, the definition of the innovation level, amount and depth of experiments, and the maturity of concepts are necessary to balance resources and design space. It was concluded that there are still opportunities regarding techniques and methods to plan and manage this compatibility. The fact that the SBD demands more resources than the PBD can be a decisive factor for those who decide to adopt this strategy. Advancing knowledge towards solutions to this problem is essential for the dissemination of SBD.

Knowledge management is approached mainly by techniques for design space mapping in several publications, including trade-off curves. An opportunity was identified by introducing the possibility of different abstraction levels in design space representation. Furthermore, another opportunity arose regarding how to store and reuse knowledge in SBD environments. Regarding quantitative, computational and/or engineering-oriented models it was concluded that major focus is imposed on the screening of concepts and techniques for filtering and communicating the design space during the NDP. The most applied technique is fuzzy arithmetic.

It was identified four reviews published in the last years regarding SBD. The reviews performed by Specking et al. (2018); Shallcross et al. (2020a) and Dullen et al. (2021) have a different scope, focusing on specific environments as complex systems or quantitative models. The review by Toche et al (2020) sought to present theories, models and methods for SBD. Nevertheless, this research includes more recent literature on SBD since the bibliographic review made by Toche et al. (2020) contains works published prior to 2017. Furthermore, they analysed the content of 24 works whilst this research analyses 121 different models. Therefore, it was concluded that the reviews published in the last years offer a limited content that may be suitable to guide research in the areas of study addressed by the authors. Nevertheless, paving the way for a comprehensive model for SBD means carrying out a complete scan of the literature so that a real overview of gaps can be obtained to foster the advancement of knowledge in the field.

Among the gaps pointed out by the authors in previous reviews, the following stand out: (1) Computational data storage, lack of starting information, limited prototyping capability, computational limitations, data limitations, resource constraints and the time to learn a particular method (Dullen et al., 2021); (2) Comprehensive methodologies to SBD combining requirements development, MBSE, uncertainty modelling, multiresolution modelling, adversarial analysis and program management (Shallcross et al., 2020a); (3) mathematical methods to define sets, assess value of points, explore the design trade-space and eliminate sets (Specking et al., 2018); (4) product development stages beyond conceptual design, SBD front-loading process, knowledge management, prototyping and testing management, interactions between subsystems teams and platforms development, lack of holistic models that support cross-domain communication, overlapping, narrowing and refinement of the sets (Toche et al., 2020).

It can be observed that even though some authors conclude that there is an absence of comprehensive methods for SBD, and the literature is concentrated in the early stages, important conclusions about what is missing to achieve a holistic managerial method for SBD were not presented. Based on this, it can be concluded that the relevance of this study is to thoroughly scan the literature and determine which models were proposed for SBD, analyse and indicate the main knowledge gaps and research opportunities towards a comprehensive method for SBD, denote the main contributions made in the literature and finally, provide recommendation for future works.

This research enabled the identification of many gaps that may hamper SBD implementation efforts. It was observed that most of the gaps found represent connections between information, steps, and activities of the SBD. It is a consequence of the dispersion of knowledge in the field and the absence of holistic and comprehensive models. Even if the models in the literature do not present conflicting views and are complementary, it is necessary to advance towards the development of models that connect and close the development process in SBD environments. This scenario implies difficulty for development teams to adopt this strategy, even though its superiority over traditional product development approaches is known and recognised. The main contributions and gaps found in literature enabled 12 recommendations for future works in the knowledge field.

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