UNIVERSIDADE FEDERAL DE SANTA CATARINA
CENTRO DE TECNOLÓGICO
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA MECÂNICA

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MANAGERIAL MODEL AND PROCESS FOR SET-BASED DESIGN

Florianópolis
2023

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Managerial Model and Process for Set-Based Design

Tese submetida ao Programa de Pós-Graduação em Engenharia Mecânica da Universidade de Santa Catarina como requisito parcial para a obtenção do título de Doutora em Engenharia Mecânica.

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Florianópolis

2023

Oliveira, Mayara Silvestre de
Managerial model and process for set-based design / Mayara Silvestre de Oliveira ; orientador, Fernando Antônio Forcellini, coorientador, Jader Riso Barbosa Jr., 2023.
180 p.

Tese (doutorado) - Universidade Federal de Santa Catarina, Centro Tecnológico, Programa de Pós-Graduação em Engenharia Mecânica, Florianópolis, 2023.

Inclui referências.

1. Engenharia Mecânica. 2. Lean thinking. 3. Desenvolvimento de produtos. 4. Inovação. I. Forcellini, Fernando Antônio. II. Barbosa Jr., Jader Riso . III. Lozano, Jaime Andrés IV. Universidade Federal de Santa Catarina. Programa de Pós-Graduação em Engenharia Mecânica. V. Título.

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Managerial Model and Process for Set-Based Design

O presente trabalho em nível de Doutorado foi avaliado e aprovado em 5 de maio de 2023, pela banca examinadora composta pelos seguintes membros:

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Certificamos que esta é a versão original e final do trabalho de conclusão que foi julgado adequado para obtenção do título de Doutora em Engenharia Mecânica.

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ACKNOWLEDGEMENTS

Maksimovic (2013) said that the true beauty of scientific research becomes evident at the precise moment it is too late to turn back. Seven years of exploring and experimenting showed me that it could not be more correct. The deeper you go into the frontier of knowledge, the more you understand the importance and the necessity of continuing to do so. The harsh and prickly journey moulds the researcher to see and think differently, and everything becomes a learning possibility.

First and foremost, I would like to thank my mother for her limitless love and support and my husband, who believed and encouraged me to go further. I acknowledge and am sincerely grateful for my advisors, who believed in my ideas and welcomed me as a Doctoral and master's Student. Prof. Dr. Fernando Antônio Forcellini gave unconditional support and guidance and taught me a lean and learning mindset. Prof. Jader Riso Barbosa Jr. and Prof. Jaime Andrés Lozano Cadena believed in the benefits Lean Product Development could bring and welcomed my research to Join PoloMag.

I would like to thank my friends and family, who kept me motivated and gave me inner peace in needed situations. Many people are involved somehow in this accomplishment, but most of all, my colleagues at PoloMag contributed enormously to my research. I would like to express my deep gratitude to Guilherme Fidelis Peixer, M. Sc, who helped me to delimit and demonstrate the technical perspective of the application case and joined me in the mission to advance Set-Based Design through our publications.

I also recognise my colleagues who adopted and believed in my research: Alan Nakashima, Dr., Bernardo Vieira, Henrique Nevez Bez, Dr. (*in memoria*), Gusttav Lang, Higor Teza, Fábio Fortkamp, Dr., Luís Felipe Cattelan, Joana da Silva, Gislaine Hoffmann, Diego dos Santos, Pedro Cardoso, Sergio Dutra, Natália de Sá, Ricardo Calomeno, and Laryssa Antunes, Marcelo Rosa, Paloma Boeck, Dra., and Prof. Cristiano Teixeira.

I thank my evaluation committee, Prof. João Espindola and Prof. Milton Pereira, who supported me by evaluating my master's Thesis and Doctoral Dissertation, and finally, Prof. Luis Trabasso, who gave an enormous contribution to LPD, inspiring this research. I acknowledge the Federal University of Santa Catarina (UFSC), the Graduate Program in Mechanical Engineering (PosMec), and Polo, Research laboratories for emerging technologies in cooling and thermophysics, for providing world-class education and infrastructure to the development of this work. Financial support from the CNPq agency, Embraco, Codemge, and Embrapii is duly acknowledged.

"The scientific man does not aim at an immediate result. He does not expect that his advances ideas will be readily taken up. His work is like that of a planter, for the future. His duty is to lay the foundation of those who are to come and point the way."

(Tesla, 1934)

ABSTRACT

Lean Product Development (LPD) emerged as the next step organisations must take toward a Lean Enterprise. LPD is complex to implement and demands a set of well-defined enablers, which are very difficult to adopt. Added to this scenario is the insipient knowledge background and lack of a consistent theoretical and practical basis, being Toyota the only case of a successful combination of lean tools and practices for well-succeeded product development. Set-Based Design (SBD) is the backbone of LPD, representing its most fundamental element, guiding all design cadence and flow. Nevertheless, the complexity of SBD implementation forms the major barrier to LPD dissemination since more than just a prescription of activities is behind its success. SBD preconises experimentation beyond the project to learn with the process instead of seeking operational efficiency. As a result, it finds more resistance among developers as its implementation consumes far more resources than traditional strategies. This research is motivated by the necessity to advance in SBD, paving the way for successful cases of LPD in the most variated environments and products. This Doctoral Dissertation aims to present a managerial model and process for SBD, providing guidelines for its implementation and organising knowledge regarding this field of study. First, a comprehensive in-depth review of the literature was undertaken to identify the current state-of-the-art. Based on this, opportunities from a managerial and engineering-oriented perspective were identified, originating guidelines for the proposal of a managerial model and process for SBD. Finally, the proposal was studied in real-world product development through action research. Value deployment and definition, model-based trade-off-curves, hybrid development strategy, and the Toyota Kata applied to product development formed a framework for designing the product in an integrated manner, building knowledge to make decisions slowly, supported by data. Separating subsystems into domains assisted in focusing efforts and resources on the most critical parts. The managerial insights from this Dissertation can assist decision-makers in overcoming barriers to SBD adoption. It encourages practitioners to adopt SBD by providing a clear perspective of benefits and implementation paths.

Keywords. Set-Based Design. Lean Product Development. Quality Function Deployment. Value. Innovation. Technology Readiness Level.

RESUMO

O Lean Product Development (LPD) representa o caminho para uma organização Lean. O LPD é complexo e exige um conjunto de elementos, que são muito difíceis de adotar. Soma-se a esse cenário uma base de conhecimento incipiente e a falta de fundamentos teóricos e práticos consistentes, sendo a Toyota o único caso de combinação bem-sucedida de ferramentas e práticas para o desenvolvimento Lean de produtos. Set-Based Design (SBD) é a espinha dorsal do LPD, representando seu elemento mais fundamental, orientando toda a cadência e fluxo do projeto. No entanto, sua complexidade constitui a principal barreira para a disseminação do LPD, pois mais do que apenas uma prescrição de atividades está por trás de seu sucesso. A SBD preconiza a experimentação além do projeto para aprender com o processo ao invés de buscar eficiência operacional. Como resultado, encontra mais resistência entre os desenvolvedores, pois sua implementação consome muito mais recursos do que as estratégias tradicionais. Esta Pesquisa é motivada pela necessidade de avançar em SBD, abrindo caminho para casos de sucesso de LPD nos mais variados ambientes e produtos. Esta Dissertação tem por objetivo apresentar um modelo e processo gerencial para a SBD, orientando sua implementação e organizando o conhecimento sobre esta área de estudo. Primeiro, uma revisão aprofundada da literatura foi realizada para identificar o estado da arte atual. A partir disso, foram identificadas oportunidades sob uma perspectiva gerencial e diretrizes foram derivadas para a proposição de um modelo e processo gerencial para a SBD. Por fim, a proposta foi estudada no desenvolvimento de produtos por meio de pesquisa-ação. O desdobramento e definição do valor, trade-off-curves, estratégia de desenvolvimento híbrido e o Toyota Kata aplicado ao desenvolvimento de produto formaram uma estrutura para projetar o produto de maneira integrada, construindo conhecimento para tomar decisões lentamente, apoiadas em dados. A separação dos subsistemas em domínios ajudou a concentrar esforços e recursos nas partes mais críticas. Os insights gerenciais desta Dissertação podem auxiliar os decisores a superar as barreiras para o SBD. Pode encorajar os profissionais a adotar o SBD, fornecendo uma perspectiva clara dos benefícios e caminhos de implementação.

Palavras-chave: Set-Based Design. Lean Product Development. Quality Function Deployment. Valor. Inovação. Technology Readiness Level.

Resumo Expandido

Introdução

O Lean Product Development (LPD) representa o caminho para uma organização Lean. O LPD é complexo e exige um conjunto de elementos, que são muito difíceis de adotar. Soma-se a esse cenário uma base de conhecimento incipiente e a falta de fundamentos teóricos e práticos consistentes, sendo a Toyota o único caso de combinação bem-sucedida de ferramentas e práticas para o desenvolvimento Lean de produtos. Set-Based Design (SBD) é a espinha dorsal do LPD, representando seu elemento mais fundamental, orientando toda a cadência e fluxo do projeto. No entanto, sua complexidade constitui a principal barreira para a disseminação do LPD, pois mais do que apenas uma prescrição de atividades está por trás de seu sucesso. A SBD preconiza a experimentação além do projeto para aprender com o processo ao invés de buscar eficiência operacional. Como resultado, encontra mais resistência entre os desenvolvedores, pois sua implementação consome muito mais recursos do que as estratégias tradicionais. Esta Pesquisa é motivada pela necessidade de avançar em SBD, abrindo caminho para casos de sucesso de LPD nos mais variados ambientes e produtos.

Objetivos

Esta tese tem como objetivo apresentar um modelo e processo gerencial para a SBD, fornecendo diretrizes para sua implementação. Para alcançar o objetivo principal desta pesquisa e obter os resultados esperados, os principais objetivos específicos são identificar os modelos e frameworks para SBD na literatura e analisar as principais lacunas e contribuições, fornecer diretrizes e propor um modelo e processo gerencial para SBD e implementar o modelo através de pesquisa-ação no desenvolvimento de um produto de inovação tecnológica.

Metodologia

Propor um modelo e processo que represente uma contribuição significativa para o campo da pesquisa com potencial para organizar e abrir caminho para a consolidação do conhecimento significa realizar uma revisão de literatura aprofundada, completa e abrangente, impondo poucas restrições. Assim, a revisão da literatura seguiu um método estruturado, replicável e sistemático chamado RBS Roadmap, selecionado por sua aderência à área de gestão de operações, à qual esta pesquisa pertence. Após a revisão, as publicações foram analisadas e classificadas de acordo com o tipo de modelo ou framework apresentado e conteúdo, considerando entradas, saídas ou o processo de afunilamento de soluções da SBD. Uma visão geral das concentrações e ausências de trabalhos em aspectos específicos da SBD foi obtida por meio da elicitação das principais atividades, etapas e ferramentas prescritas pelos autores. Por fim, um esboço de um processo gerencial para a SBD foi construído com as principais atividades e etapas identificadas entre os modelos gerenciais. Dessa forma, o modelo foi proposto e implementado em um caso real de desenvolvimento de produto após a pesquisa-ação. A pesquisa-ação é uma metodologia que segue um ciclo em que a prática é aprimorada pela oscilação sistemática entre a atuação no campo da prática e sua investigação. Ao planejar, implementar, descrever a mudança e avaliar a melhoria, o pesquisador aprende mais sobre o processo por meio da prática e da investigação.

Resultados e Discussões

O desdobramento e definição do valor, trade-off-curves, estratégia de desenvolvimento híbrido e o Toyota Kata aplicado ao desenvolvimento de produto formaram uma estrutura para projetar o produto de maneira integrada, construindo conhecimento para tomar decisões lentamente, apoiadas em dados. A separação dos subsistemas em uma abordagem híbrida de desenvolvimento ajudou a concentrar esforços e recursos nas partes mais críticas do produto.

Considerações Finais

A relevância e originalidade desta Tese de Doutorado são evidenciadas pela revisão abrangente, aprofundada, sistemática e estruturada da literatura. Possibilitou a derivação de diretrizes e requisitos para garantir o avanço no campo da SBD e a comparação e posicionamento da pesquisa proposta frente ao estado da arte. A SBD representa um interesse crescente na literatura, com aumento consistente de publicações. Isso se reflete no número de revisões que representam um esforço para organizar e fornecer diretrizes para novas ferramentas, métodos e modelos para apoiar sua adoção. Em comparação aos trabalhos de revisão em SBD já feitos, a revisão da literatura que fundamenta esta tese é a de maior amplitude, analisando 121 publicações, e abrange todos os modelos e frameworks independente do ambiente, tipo de sistema ou estágio de desenvolvimento. Os insights gerenciais desta tese podem auxiliar os decisores a superar as barreiras para

o SBD e encorajar profissionais a adotar esta estratégia, fornecendo uma perspectiva clara dos benefícios e caminhos de implementação.

Palavras-chave: Set-Based Design. Lean Product Development. Quality Function Deployment. Valor. Inovação. Technology Readiness Level.

FIGURES

TABLES

ABBREVIATIONS

AMR	Active Magnetic Regenerator
CAD	Computer-Aided Design
CC	Current Condition
CE	Chief Engineer
CHTF	Chosen-to-fit
CK	Coaching Kata
CR	Customer Requirements
CS	Concept Screening
CUTF	Custom-to-fit
DS	Design Space
DR	Deliverable Roadmap
EC	Engineering Characteristics
EF-M	Enhanced Function Means
FMEA	Failure Mode and Effects Analysis
HEx	Heat Exchangers
HS	Hydraulic System
IE	Integration Events
IK	Improvement Kata
IPT	Integrated Product Teams
LC	Learning Cycle
LPD	Lean Product Development
LI	Level of Innovation
LIC	Labelled Interval Calculus
MC	Magnetic Circuit
MCDA	Multi Criteria Decision Making
MCE	Magnetocaloric Effect
MCM	Magnetocaloric Materials
MCSP	Multi Criteria Sorting Problem
ML	Machine Learning
MR	Magnetic Refrigeration
MRU	Magnetic Refrigeration Unit
NDP	Narrowing Down Process
PBCE	Point Based Concurrent Engineering
PBD	Point Based Design
PBSE	Point Based Serial Engineering
PDCA	Plan-Do-Control-Act
PDP	Product Development Process
PLM	Product Lifecycle Management
QFD	Quality Function Deployment
RBM	Responsibility-Based Management
R&D	Research and Development
SBCE	Set Based Concurrent Engineering
SBD	Set Based Design
SBR	Systematic Bibliographic Review
TBM	Task-Based Management
TC	Target Condition
TK	Toyota Kata
TKDev	Toyota Kata Development
ToC	Trade-off Curves
TRL	Technology Readiness Level

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CHAPTER 1

RESEARCH FOUNDATIONS

The motivation of this research is the insipience of the literature regarding a comprehensive and managerial perspective for Set Based Design (SBD). This scenario, added to the complexity of its implementation due to its learning orientation character, hampers the adoption of the strategy, even though its superiority over traditional product development approaches is acknowledged. This research addresses the difficulties in connecting the contributions provided in the literature to form a complete product development strategy, providing guidelines for a well-established SBD.

This Chapter presents the foundations of this research. It is organised to provide an overview of the knowledge pertaining to this field of study and discuss the originality and contribution of this Doctoral Dissertation to advancing knowledge in SBD and its socio-economic implications. The context, research motivation, problems addressed, goals, methodology, and the importance of the present research work are provided in five sections. The Chapter conclusion links the Doctoral Dissertation structure with the research methodology and the literature gaps in an in-depth review.

1.1. BACKGROUND AND RESEARCH MOTIVATION

Organisations are compelled to be flexible, competitive, and innovative due to socioeconomic factors, leading to a growing interest in lean initiatives, especially product development (TOCHE, 2017). The necessity to change traditional product development techniques to deliver more value is reflected in the consistent increase of publications on SBD over the years (TOCHE; PELLERIN; FORTIN, 2020; SHALLCROSS *et al.*, 2020a; DULLEN *et al.*, 2021). Nevertheless, the implementation attempts of Lean Product Development (LPD) and its enablers, such as SBD, are yet insipient, and few studies provide a practical and detailed approach to its practices (HOPPMANN *et al.*, 2011; LEON; FARRIS, 2011; TOCHE, 2017; TARIQ, 2018; TOCHE; PELLERIN; FORTIN, 2020). Furthermore, except for Toyota, the literature does not address a combination of LPD tools and practices for well-succeeded product development (AL-ASHAAB *et al.*, 2016a; AMMAR *et al.*, 2017; TOCHE, 2017; OLIVEIRA, 2017).

Research in LPD focuses on its underlying principles and concepts rather than converging to methodologies for its implementation, integration of tools, coordination strategies, and performance measures (HOPPMANN *et al.*, 2011; LEÓN; FARRIS, 2011; TOCHE, 2017; OLIVEIRA, 2017). The insipience of LPD is translated by the lack of a consistent guiding theory basis (HOPPMANN *et al.*, 2011; TOCHE; PELLERIN; FORTIN, 2020) and the complexity of SBD implementation since more than just a prescription of activities is behind its success (AMMAR *et al.*, 2017; AMMAR *et al.*, 2018). SBD preconises experimentation beyond the project to learn with the process instead of seeking operational efficiency. As a result, it finds more resistance among developers as it consumes far more resources than traditional strategies (SCHULZE, 2016; PESSOA; TRABASSO, 2017). The Narrowing Down Process (NDP) in SBD is quite costly compared to choosing a solution assisted by decision matrices (PESSOA; TRABASSO, 2017).

A comprehensive Systematic Bibliographic Review (SBR) of SBD resulted in several gaps in the literature, presenting an opportunity for further advancing this field of study. The absence of a comprehensive managerial-oriented model for SBD was evidenced by the 121 models and frameworks identified in the literature, providing guidelines for organising and orchestrating development efforts for performing the NDP. The models and frameworks generally present tools to assist in finding, selecting, and representing the Design Space (DS) and focus on specific parts and aspects of SBD. Even though many efforts were made to present early-stage methods and quantitative, computational, and engineering design-oriented models, little was advanced toward a complete process for SBD. This scenario does not favour the adoption of this convergence strategy.

The problem underpinning this research is that even though SBD superiority over traditional product development approaches is known, its implementation is hampered by the absence of general, integrated, and broad guidelines for a well-established SBD. The dispersed and unconsolidated knowledge from a managerial perspective over the subject implies difficulties in connecting the contributions provided in the literature to form a complete product development strategy, especially regarding the NDP. A comprehensive managerial model is a path to orchestrate the gradual reduction of the DS by integrating teams, concepts, tools, and elements. This study is motivated by the necessity to provide guidelines for SBD detailing the NDP and the connection between the front-loading activities in SBD, including the value deployment, planning, balancing of resources and DS, and Trade-off Curves (ToC).

1.2. OBJECTIVES

This Doctoral Dissertation aims to present a managerial model and process for SBD, providing guidelines for its implementation. The results of this research pave the way for successful cases of LPD in the most variated environments and products. Furthermore, this research seeks to organise knowledge in SBD, enabling the further advancement of the state-of-the-art toward consolidated knowledge in the field. To achieve the main objective of this research and obtain the expected results, the specific objectives were established:

1 Comprehensively, thoroughly, and deeply scan the literature regarding models and frameworks for SBD to bound state-of-the-art;

2 Identify the main gaps and contributions concerning models and frameworks for SBD from a managerial and engineering-oriented perspective;

3 Provide guidelines for a managerial model and process for SBD through the analysis of the opportunities and gaps in the literature;

4 Propose a managerial model and process for SBD based on the guidelines elicitated;

5 The implementation of the model and the outcomes in real-world product development through action research.

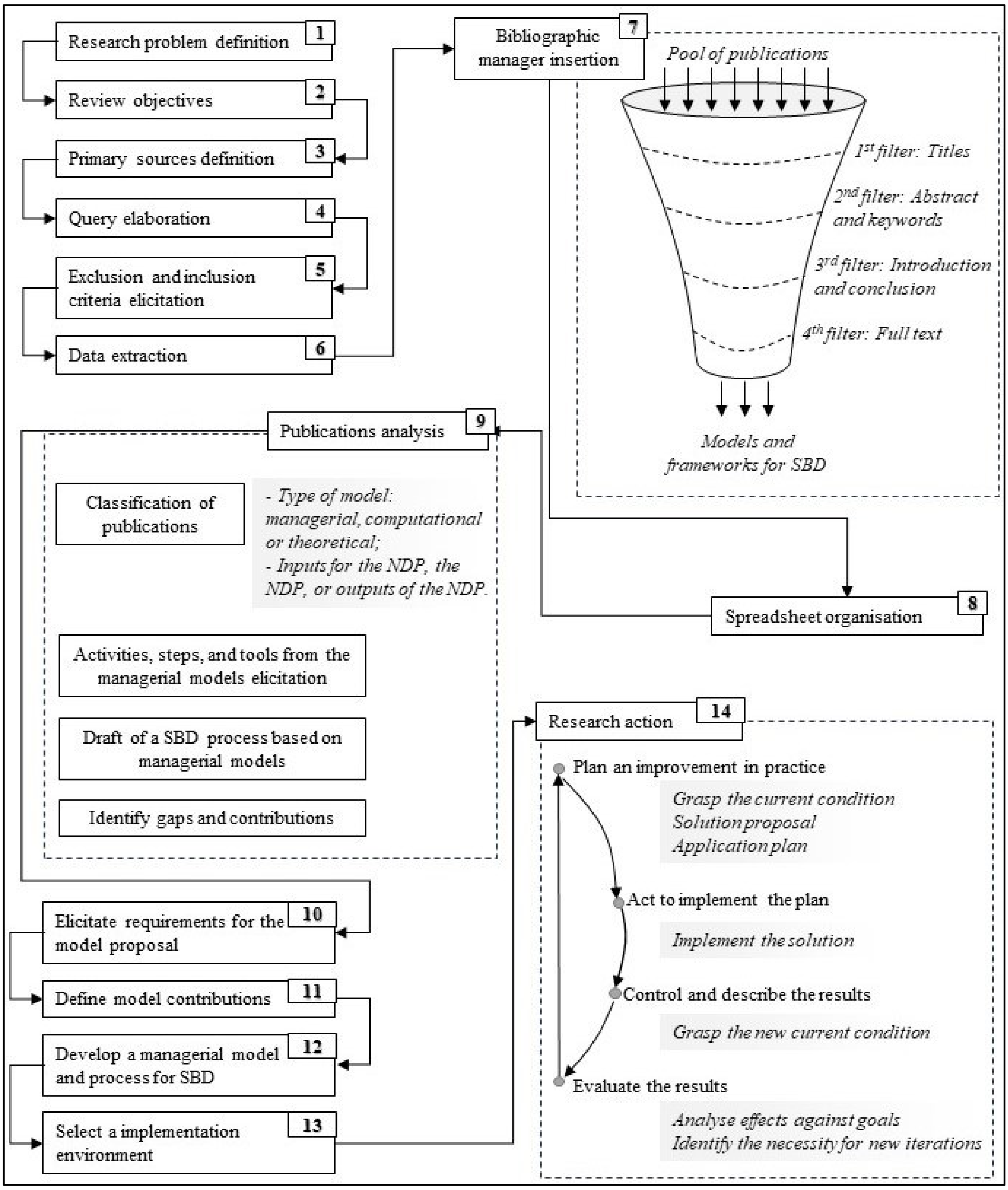
1.3. METHODOLOGICAL PROCEDURES

The methodological procedures of this Doctoral Dissertation are organised to achieve the objectives pertaining to this research. An overview of the methodology is presented in Figure 1.1. Proposing a model and process representing a significant contribution to the research field with the potential to organise and pave the way toward knowledge consolidation means performing an in-depth, complete, and comprehensive literature review, imposing few restrictions. Thus, the literature review followed a structured, replicable, and systematic method. The model proposed by Conforto, Amaral, and Silva (2011), called RBS Roadmap, was selected for its adherence to the area of operations management, to which this research belongs.

The SBR comprises eight steps, beginning with the problem and objectives definition to guide the entire review. Then, the choice of primary sources is made based on the best databases pertaining to the field of investigation. After an exploratory search, the query to extract data from the databases is defined, grasping the keywords representing the broad subjects in the literature. The inclusion and exclusion criteria are set to select publications relevant to the research. Subsequently, the query is inserted into the database searchers, and the data is extracted. A bibliographic manager assists in filtering and organising publications. First, titles are checked for adherence to the subject. Second, the abstract and keywords are read, followed by the introduction and conclusion, and, finally, the full text of the remaining works. The results are registered and classified in a spreadsheet to proceed with the analysis of the resulting references.

The research follows by analysing the publications. First, an effort is made to classify works according to the type of model or framework presented. The literature is scanned for managerial models, computational and quantitative approaches, and theoretical frameworks. Second, the publications are classified according to their content, whereas they present inputs for the NDP, address the NDP itself, or detail outputs of the process and activities to finish the SBD. An overview of concentration and absences of works regarding specific aspects of the SBD is obtained through elicitation of the main activities, steps, and tools prescribed by the authors. Finally, a draft of a managerial process for SBD is built with the main activities and steps identified among managerial models. The publication analysis results in a well-defined list of contributions and gaps in the literature enabled by the classification and organisation of works.

Figure 1.1. Methodological procedures



To better address the opportunities identified, develop a managerial model and process that represents a significant advance in SBD, and achieve the objectives of this research, requirements for the model were elicitated based on the literature review. It assisted in defining the contributions of the proposal and guiding its elaboration. The main elements considered a ‘must be' in the model, such as fundamental elements of SBD, widely accepted practices and tools, and absences in the literature that compromise SBD adoption, underpinned the model creation. The model focuses on non-explored areas in SBD. This research aims to address aspects, problems, and unprecedented procedures. Since the subject related to this research has a scarce background in the literature, it is necessary to perform a study that enables the construction and validation of results in a real-world environment. Thus, this research is suitable for being conducted through action methods using action strategy as the path to acquire scientific knowledge. Six research methods based on action are presented in Table 1.1.

Table 1.1. A comparison of action methods using action strategy criteria

Method	Purpose	Researcher role	Epistemology & Discourse	Assessment	Level of interference
Action research	Involvement and improvement	Process guide	Use of data-based, actionable knowledge	Appropriateness of method and on the problem solution extent	Data driven, general low inference, higher level testing.
Participatory research	Quality of life improvement and realisation of democratic ideals	Partner performing supportive functions	Knowledge based on expanded epistemological theory	Evaluation for participatory research to create a reflection–action cycle	Progressing from problem-solving to problem-posing
Action learning	Changing of systems through action and reflection	Passive, acting as mirror to assist in learning	Problem-solving, and problem-framing, making meaning of experience	Change at individual, team, or system level depending on focus	Generally medium
Action science	Changes in reasoning and behaviour leading to human development	Active, interrupting practices, provoking reflection, modelling behaviour	Reflecting in action, making explicit tacit theories-in-use	Effectiveness, learning capability, and systemic change	Up and down the ladder of inference
Action inquiry	Feedback to change outcomes, behaviour, and vision	Reconciling, blending passion, dispassion, and compassion	Seeking and suffering awareness of incongruities among the territories of experience	Performance assessment, systems effectiveness, and the mission/vision	Testing alignment, and real-time outcomes
Cooperative inquiry	Practical knowing in the service of human flourishing	Initiates the inquiry process facilitating cooperation	Personal, organisational, cultural, depending on focus. Co-created findings.	Assessment built in through the process of research cycling	From exploratory inquiry to experimental testing

Source: Adapted from Raelin (1999)

This research has a data-based character, being the researcher, a process guide performing action cycles to stimulate the participation of the organisational members affected by the problem. Furthermore, the proposal verification and analysis are based on its appropriateness and the extent to which the original problem is solved. Based on this scenario, the methodology adopted for this study is action research as it preconises the collaborative work with the application environment to observe, understand, and modify environmental conditions to lead the direction of the research (DICKENS; WATKINS, 1999). The researcher then proposes a modification to the system and analyses the outcomes. Iterations are performed until the problem is exhausted.

Action research is a methodology that follows a cycle in which practice is improved by systematic oscillation between acting in the field of practice and its investigation. By planning, implementing, describing the change, and evaluating the improvement, the researcher learns more about the process through practice and investigation (TRIPP, 2005). The action research follows the Plan-Do-Control-Act (PDCA) cycle. The research paradigm in this Doctoral Dissertation is qualitative, empirical, positivist, and based on a model. It is related to the phenomenological inquiry (qualitative research) as it is predominantly interpretative, inductive, emerging meaning and themes from the data analysis collected through interviews, observations, and experience, backed by research action premises (TOCHE, 2017).

The research action begins by grasping the Current Condition (CC) of the application environment to establish an implementation plan. Then, the planning is executed by changing the traditional practices. Finally, the effects in practice are controlled and evaluated based on the problem that the research aims to solve. The cycle continues until the implementation plan is complete and results achieved (TOCHE, 2017). The data collection and the observable effects are planned according to criteria enabling to judge the research validity, reliability, and trustworthiness.

1.3.1. Application environment: The development of a magnetic refrigeration unit

The application environment is the development of a Magnetic Refrigeration Unit (MRU), held by POLOMAG, a research group of the National Institute of Science and Technology in Refrigeration and Thermophysics (INCT - POLO), located in the Department of Mechanical Engineering of the Federal University of Santa Catarina. The goal of the group is to develop new cooling technologies based on the Magnetocaloric

Effect (MCE), which is the thermal response of some materials when subjected to a variation of a magnetic field (PEIXER, 2020). Magnetic Refrigerators (MR) are composed of an Active Magnetic Regenerator (AMR), a Magnetic Circuit (MC), a Hydraulic System (HS), and Heat Exchangers (HEx) (TREVISOLI *et al*., 2016; PEIXER, 2020).

The research group began the implementation of the LPD in 2017 through the Master Thesis that preceded this Doctoral Dissertation (see OLIVEIRA, 2017). The motivation to adopt lean initiatives was the difficulty in integrating and managing the development of products. The Chief Engineer (CE) followed traditional management techniques that did not favour grasping the current state of the project. These techniques generally consist of diagrams presenting lots of information, posing difficulties in visualising and controlling the process. Innovative products are complex design environments that demand maximal team integration. Without the correct approach to manage the PDP, it becomes an impossible task.

Several research groups are seeking to advance in the technology by developing new materials and designing and analysing crucial components such as MC and AMR. Nevertheless, even after decades of Research and Development (R&D), the technology is not yet commercially available, and the prototypes did not achieve the expected performance (PEIXER, 2020). The motivation to replace traditional compression components for systems based on the MCE lies in the absence of harmful gases adopted in conventional vapor compression systems, the potential to achieve the desired operating performance, and its recyclable nature (PEIXER, 2020).

Highly innovative projects are subject to considerable uncertainties and risks, the inexperience of developers, and little previous knowledge. Furthermore, the novelty of the technology imposes a scenario without qualified suppliers available and high cost of raw materials compared to the project budget. It implies the necessity of computational tools as the basis for the process of learning and development. Furthermore, it is a mandatory requirement to seek innovation to design. Thus, SBD is a suitable strategy for the product. Committing to a particular solution early in development means facing a high risk of failure since the designers have no previous knowledge about the values the parameters will assume to deliver the required performance. SBD supports the design of new technologies as it keeps the DS open as long as possible, stimulating innovation and reducing risks.

1.3.2. Analysis of the results and data collection

The efficiency of the model and process for SBD comes from its ability to enable an environment of learning and innovation, where the DS can be explored to find the most suitable design alternatives for the subsystem to deliver the project goals. Based on the gaps and opportunities in the literature and the requirements for the model and process proposal, some results are especially relevant to what pertains to this study, as presented in Table 1.2. Furthermore, these results grasp the main principles and elements related to the SBD.

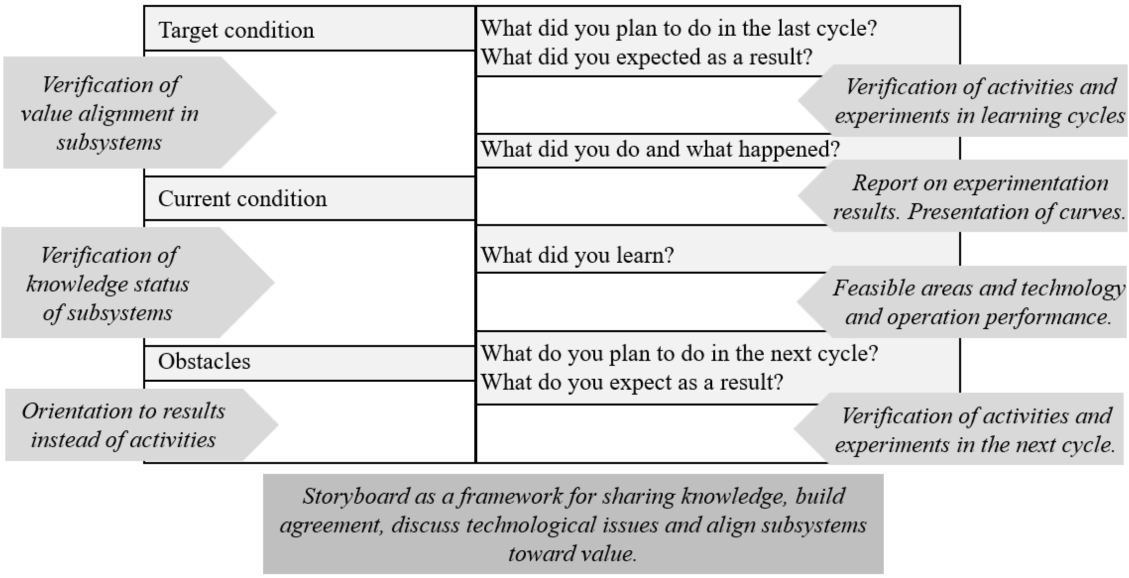
Table 1.2. Expected outcome of the research action

Expected results	Expected outcome observable in the research action
Balancing resources and DS to execute SBD even with considerable restrictions	It was possible to classify subsystems in SBD and PBD and the integration between them was verified.
Providing a structure where ToC assist in the NDP and in checking compatibility among subsystems	ToC clearly represent the feasible area of the DS. ToC were presented and discussed in the Integration Events (IE). ToC enabled DS narrowing.
Enabling consistent value deployment to align design efforts toward value and manufacturing integration in the PDP	Value is fully understood in all subsystems. Manufacturing is contemplated in the NDP.
Registering and storing valuable knowledge to foster learning and sharing	Knowledge produced during leaning cycles is consistently organised and systematised.
Performing effective IE and structured Learning Cycles (LC)	IE and LC are connected. They present a structure enabling discussion and DS narrowing. DS agreement was built.
Avoid commitment to a particular concept early in the development and gradually and smoothly reduce DS	The DS was gradually reduced, and no rework and correction loops were observed.
Fostering test-before-design through experiments or computational simulations with an acceptable uncertainty	Experiments and simulations were performed to screen DS instead of finding an optimal solution.

Documents and observations of the researcher form the collection that provides the main results of the model and process for SBD. Crucial tools and curves generated during the development were gathered as well. The portfolio of documents and observations reported enabled observing the research outcomes. General data in meetings, IE, and kata storyboards were collected and registered from the perspective of the researcher. Furthermore, interviews with developers were conducted to grasp the perception of designers about the PDP.

The most crucial result of the model and process for SBD is the capacity to perform the narrowing-down of the DS. Special attention is given to the 'test-before-design' mindset to avoid early decision-making and underpin experimentation with different configurations of the subsystems and regions of the DS enabling its reduction. Data from 65 IE were gathered and 238 storyboards were analysed. Each storyboard provides information, as presented in Figure 1.2.

Figure 1.2. Observations in the storyboards of subsystems



1.4. RELEVANCE, IMPLICATIONS, AND OUTLINE OF THE RESEARCH

The relevance and originality of this Doctoral Dissertation are evidenced by the comprehensive, in-depth, systematic, and structured review of the literature. It enabled the derivation of guidelines and requirements to ensure the advance in the field of SBD and the comparison and positioning of the proposed research against the state-of-the-art. The SBD represents a growing interest in the literature, with a consistent increase in publications. It is reflected by the number of reviews representing an effort to organise and provide guidelines for new tools, methods, and models to support its adoption.

In recent years four relevant reviews were published in the literature (see Table 1.3) (DULLEN *et al.*, 2021; SHALLCROSS *et al.*, 2020a; SPECKING *et al.*, 2018b; TOCHE; PELLERIN; FORTIN, 2020). Nevertheless, none presents a review with such depth and extension, identifying gaps that may discourage SBD adoption, especially from a managerial perspective. Specking *et al*. (2018b) reviewed methods for set definition, elimination, and trade-off analytics, resulting in 34 papers.

Table 1.3. Reviews regarding SBD in recent years

	Specking *et al.* (2018b)	Shallcross *et al.* (2020a)	Toche, Pellerin, and Fortin (2020)	Dullen *et al.* (2021)	This research
Objective	Methods for trade-off analytics	State-of-practice, complex system design	Theories, models, and methodologies for 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

Source: Oliveira *et al*. (2022a)

Dullen *et al*. (2021) reviewed and classified 118 publications on SBD quantitative 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). 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 in complex systems, expanding the search beyond SBD.

Toche, Pellerin, and Fortin (2020) aimed to identify theories, models, and methodologies for SBD, considering a wide scope. Regarding the works from Specking *et al*. (2018b), 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. Furthermore, compared to the review by Toche, Pellerin, and Fortin (2020), this research analyses 121 publications and includes more recent literature on SBD since their bibliographic review contains works published before 2017.

To propose a managerial model and process for SBD and further advance knowledge in the field, it is necessary to carry out a complete scan of the literature to obtain a genuine overview of gaps to foster the advancement of knowledge in the SBD. Therefore, it is necessary to thoroughly scan the literature and determine which models were proposed for SBD, analysing and indicating the main knowledge gaps and research opportunities, which denote the relevance of this research.

A managerial process and model for SBD capable of filling knowledge gaps and providing guidelines for SBD implementation and orchestration is also a relevant contribution. It marks the advancement of the understanding of SBD from the most general aspects to the most specific aspects. Especially concerning the NDP, by showing not only the general process but also the specificity of procedures within the IE and activities and connections of inputs enabling the DS reduction. The environment of application of this research also represents an unprecedented case of SBD adoption, highlighting one more aspect that underpins the relevance of this Doctoral Dissertation.

New and unexplored environments, types of products, and organisational structures are opportunities to enable the strategy to be more widely used, and successful reports on its implementation may emerge, not just from Toyota. The potential for SBD in highly innovative projects is remarkable. Its learning orientation, test-before-design, and DS exploration nature reduces risks and raises the chances of finding a suitable solution for complex problems. Nevertheless, the literature approaches only cases with consolidated technologies and knowledge.

Finally, this research has the potential to disseminate and increase successful SBD adoptions by organising and gathering knowledge from a managerial perspective. It implies a better scenario for managers and leaders to set and orchestrate a Product Development Process (PDP) for SBD. Closing the gaps in the literature by proposing a process and model for a complete SBD that clarifies how the strategy works means encouraging its adoption in different environments and products, from which the social implications of this research arise.

Since SBD promotes an environment of innovation, encouraging the adoption of this strategy facilitates innovation and problem-solving with non-preconceived ideas and concepts. Furthermore, it fosters learning and decision-making based on proven facts. It leads to the emergence of new technologies or the use of different technologies to solve the same design problem.

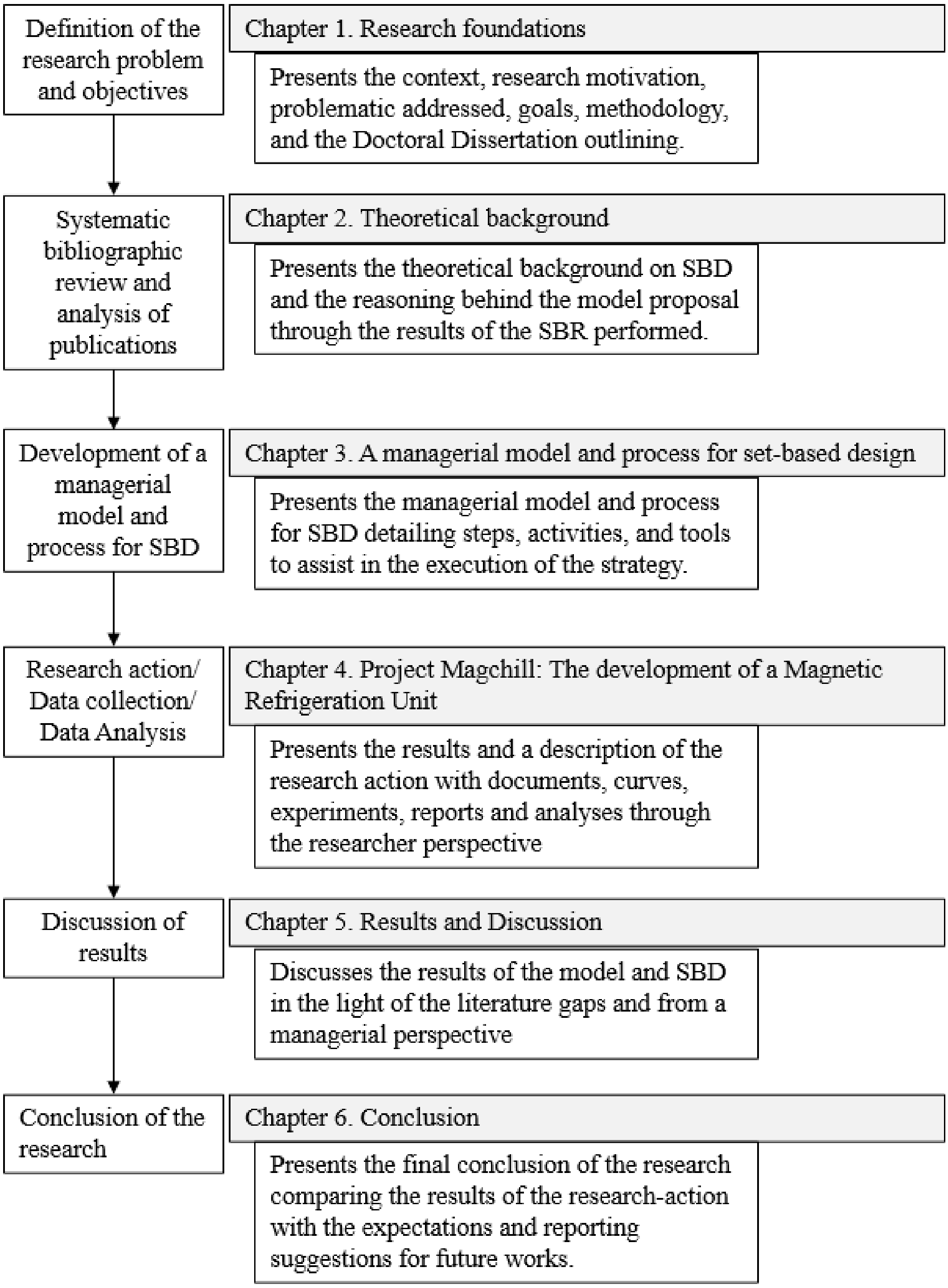
The economical implication is regarding having more innovative products with a better solution at a competitive cost. The ecological implication is the possibility of introducing new clean technologies to replace older and non-ecological ones, as the application case in this Doctoral Dissertation. Finally, this study is limited to presenting an ideal state of PDP according to the precepts of the SBD. It is not within the scope of this research to encompass methods, techniques, and tools that enable the transition from a traditional development state to LPD. Furthermore, mathematical, computational, or engineering design-oriented models are not included, since these models represent most of what is proposed in the literature.

1.5. DOCTORAL DISSERTATION STRUCTURE

The chapters in this Doctoral Dissertation are organised according to the proposed research methodology through the development and application of the model. In the first Chapter, the research foundations are presented through the background and motivation, objectives, methodological procedures, and a discussion about the relevance, implications, and outline of the research. The second Chapter addresses the theoretical background pertaining to this field of study. The main concepts and principles related to SBD are provided. Furthermore, an extended description of the results of the SBR, its analysis, and the gaps and contributions in the literature are presented.

The third Chapter comprises the proposal of a managerial model and process for SBD, representing the core of this Doctoral Dissertation. The proposal is organised in sections to better address the requirements obtained through the literature analysis. The fourth Chapter reports the action research. The fifth Chapter discusses the results of the research and, finally, Chapter 6 concludes the work. Figure 1.7 presents the logical chain of ideas of this Dissertation and the links with the objectives and the requirements to guide the development of managerial models that can foster SBD implementation defined in Chapter 2.

Figure 1.3. Doctoral dissertation structure



CHAPTER 2

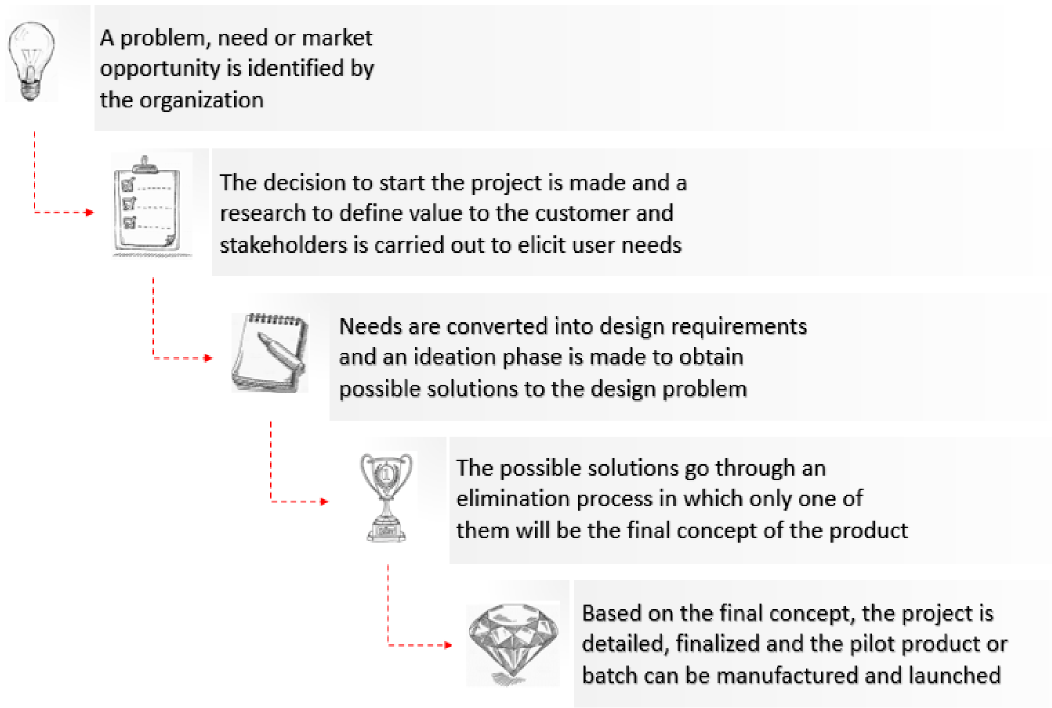
THEORETICAL BACKGROUND

This Chapter presents the theoretical background on SBD, extracting crucial aspects of the approach such as DS exploration, development flow, supporting tools, and the practices holding the DS open long into the development process through the delay of decision making. The fundaments underpinning this research are established based on a comprehensive literature review. This Chapter is organised into three parts to better approach the reasoning behind the model proposal and the results of the SBR. First, it presents the main concepts, principles, and elements regarding SBD. Second, the results of an SBR on SBD are reported. Finally, it details the state-of-the-art models and frameworks for SBD and discusses the main contributions and gaps found in the literature. It provides the requirements for the model proposed in this Doctoral Dissertation.

2.1. CONVERGENCE STRATEGIES IN PRODUCT DEVELOPMENT

The definition of product is everything a company delivers to its customers, from tangible products to services. Organisations deliver value through a PDP, transforming the product from an idea into something consumers can buy and use (RADEKA, 2013). The rationale behind PDP follows the logic presented in Figure 2.1. This process demands the extraction or convergence of a pool of alternative solutions into a final concept. The elimination process can be performed accordingly to two strategies. The first consists of deciding on the best option from the pool based on criteria analysis. This strategy is called Point-Based Design (PBD) and is the most traditional strategy in PDP. The second consists of phasing out alternatives proven unfeasible or less interesting until only one final solution remains. This strategy is known as SBD and has emerged as a solution for the problems arising from PBD.

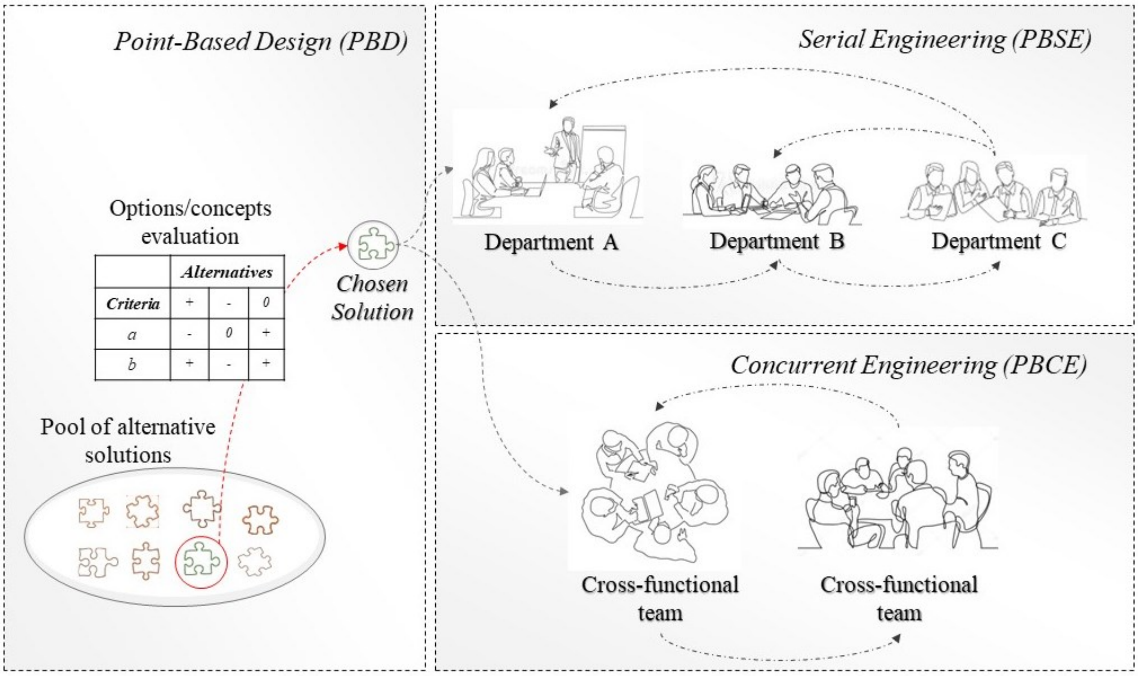
Figure 2.1. The product development process



2.1.1. Point-Based Design

The PBD strategy consists of choosing a concept for the product from a set of possible solution alternatives. The DS contains all possible values for the project parameters (MORGAN; LIKER, 2006). Before restrictions are imposed by Customer Requirements (CR) and other stakeholders, the DS is infinite, i.e., the parameters which define the product can assume any value. The term 'point-based' refers to the punctual nature of DS in PBD environments. Choosing a particular solution means committing to a specific point in the DS. PBD can be performed in a serial engineering environment (Point-Based Serial Engineering (PBSE)) or a concurrent engineering environment (Point-Based Concurrent Engineering (PBCE)), as presented in Figure 2.2.

Figure 2.2. Point-based design + serial engineering + concurrent engineering



Serial engineering is the most traditional development process, characterised by multiple departments that seek to complete their part of the project quickly and efficiently and send it to the subsequent department (PESSOA; TRABASSO, 2017). In the PBSE process, the chosen concept is partially developed and sent to the next step, which receives the project and continues the development. The process proceeds until the product is fully designed (OLIVEIRA, 2017). The PBSE logic entails problems with project alterations during development. Any design changes return to previous departments for analysis and corrections. It causes rework loops that compromise efficiency and raise development costs. Furthermore, PBSE addresses manufacturing, assembly, and maintenance issues later in the development, further increasing rework loops (PESSOA; TRABASSO, 2017)

Concurrent engineering emerged as an answer to the problems caused by serial engineering since it considers the requirements of every step of the product life cycle early in the project. Thus, the chances of developing a valuable product increase leading to a better solution to maintain, assemble, and manufacture (PESSOA; TRABASSO, 2017). Furthermore, the development is not undertaken in sequential departments but in cross-functional teams (MYNOTT, 2012). The main idea of concurrent engineering is to increase product knowledge early in development to support decision-making (PESSOA; TRABASSO, 2017).

Involving stakeholders in the early stages enables a comprehensive view of the entire product life cycle in the conceptual design phase, focusing on the optimal rather than the minimal cost by considering performance and attributes simultaneously (MAJERUS, 2016; PESSOA; TRABASSO, 2017). In PBCE environments, the chosen concept development follows through cross-functional teams considering all aspects of the product life cycle. Initially, the team analyses the solution proposed by a function or department and performs changes as needed. When the project is considered appropriate, it passes to the next step. This cycle continues until the product is designed (SOBEK II; WARD; LIKER, 1999).

Teams are better at conducting daily project activities compared to departments. Conversely, functional departments are centres of competence that support specific parts of the PDP (MYNOTT, 2012). Rework, design changes, and problems are reduced by the cross-functional teams, early involvement of stakeholders, and the consideration of product life-cycle requirements. This framework leads to a more robust design when compared to PBSE (MAJERUS, 2016). Nevertheless, PBD carries uncertainties about process convergence even in concurrent engineering environments, implying a significant amount of rework, albeit less than PBSE.

The idea that a proper analysis in the conceptual design phase leads to efficient decision-making underpins PBD (PESSOA; TRABASSO, 2017). This strategy is usual in PDP and is also known as the 'early-design-freeze policy', which means that crucial decisions are made early in the project leading to constraints and commitment to a specific solution (FORD; SOBEK II, 2005). The major problem associated with this strategy is its early decision-making nature. Decisions made at early development stages are usually not based on a solid knowledge background. It favours to a tendency to decide based on desirable things and guesswork. It may cause rework and correction loops during PDP, especially if the chosen concept is unfeasible or require design changes (OLIVEIRA, 2017).

The potential problems arising from PBD adoption go beyond poor decision-making. There is a natural tendency to avoid risky and unexplored alternatives. Hence, the most innovative solutions are generally not chosen since they have a greater chance of failure due to their ground-breaking character (PESSOA; TRABASSO, 2017). Consequently, this strategy usually does not provide an environment that encourages innovation. Furthermore, PBD sets goals early in the project, usually based on insufficient information and inside the comfort zone, which inhibits innovation, among other harms (MAJERUS, 2016; PESSOA; TRABASSO, 2017).

One of the main disadvantages of using PBD is the uncertainty regarding choosing one solution that meets all design requirements. Furthermore, the changes made during development will impact the decisions of previous steps, implying a large amount of rework and iterations (FORD; SOBEK II, 2005; INOUE *et al.*, 2013; KAO, 2006; LEE; BAE; CHO, 2012; SHAHAN; SEEPERSAD, 2010; WARD, 2011; SINGER; DOERRY; BUCKLEY, 2009).

2.1.2. Set-Based Design

SBD consists of developing sets of solution alternatives simultaneously and narrowing them down through the intersection of the DS (OLIVEIRA, 2017). The SBD, also called Set-Based Concurrent Engineering (SBCE), is the solution convergence strategy of the LPD. The term 'set-based' indicates that designers generate sets of solution alternatives and gradually filter them to a final solution (WARD *et al.*, 1995). The term 'Concurrent Engineering' defines the SBD nature of performing activities in parallel, considering all stages of the product life cycle, in cross-functional teams to accelerate the development process (KAO, 2006; LEÓN; FARRIS, 2011; PESSOA; TRABASSO, 2017). SBD is also known as SBCE because it is incompatible with serial engineering environments. Cross-functional teams and the execution of activities in parallel is crucial to the filtering process of SBD (PESSOA; TRABASSO, 2017; QURESHI *et al.*, 2010; WARD, 2007; YANNOU *et al.*, 2013).

SBD may seem inefficient, albeit four times more productive than the PBD strategy (MORGAN, LIKER; 2006; WARD; 2007). The cost of SBD adoption is equivalent to using PBD. Nevertheless, the difference between the two strategies is that

SBD is superior concerning development risks reduction and knowledge creation since it enables the study of various alternatives for the product (PESSOA; TRABASSO, 2017). Among the advantages of adopting SBD offers over PBD is the in-depth DS exploration, posing greater chances of finding a suitable solution. The chances of success are commensurate with the size of the DS explored and the experimentation. They enable a better study of interactions between product elements (MAJERUS, 2016).

SBD may present some disadvantages, such as repetitive experiments requiring extensive resources. Furthermore, not all knowledge created is used in the project, although it forms a solid knowledge base in the organisation. Managers do not consider favourable to use resources to develop unapplied knowledge (MAJERUS, 2016). Nevertheless, SBD results in an ideal solution obtained in less time and with less effort than traditional development methods (OOSTERWAL, 2010).

2.2. SET-BASED DESIGN: THE CONVERGENCE STRATEGY OF LEAN PRODUCT DEVELOPMENT

The LPD consists of problems systematically solved by product designers to maximise value added and minimise waste throughout the system (RADEKA, 2013). The elements in LPD responsible for maximising the value delivered are the system designer, SBD, Responsibility-Based Management (RBM), and the integrated product teams (KENNEDY, 2003). The SBD is the strategy of solution convergence of LPD, keeping the DS open throughout the PDP rather than choosing a particular solution from the beginning (PESSOA; TRABASSO, 2017). Hence, a strong culture of systematic problem-solving is necessary, rather than just firefighting (PESSOA; TRABASSO, 2017; RADEKA, 2013).

Developers must have strong problem-solving skills and the leadership needs to ensure that they are imprinted in their behaviour. Culture is the basis for SBD, being the most complex LPD element to embrace (MORGAN, LIKER; 2006; WARD; 2007). Separating SBD and LPD is quite complex as the LPD has crucial features and elements that enable SBD. The main enablers of SBD are the system designer or CE, the value deployment to different levels of the product, RBM, IE, LC, knowledge creation as the core of development, rapid prototyping, and testing. It is not possible to adopting SBD without this structure (OLIVEIRA, 2017).

The CE is responsible for the product and the project results, from the first stage of development to market delivery. The requirements for holding this position are the capability to direct all development efforts and dictate the concept and style of the product based on deep knowledge and experience (MORGAN; LIKER, 2006; SOBEK II; WARD; LIKER, 1999). Communicating development goals and aligning all development efforts towards them is the main responsibility of the CE (PESSOA; TRABASSO, 2017). The value must be shared and deployed into objectives for all development teams (MORGAN; LIKER, 2006). Thus, the CE leads the value deployment of the system (product) for each subsystem, component, and part until the level of production and quality. Each subsystem establishes goals based on its desired performance, constraints, and impact on other parts of the product.

Traditional product development is planned based on the premise that development tasks are predictable and consistent. Thus, a team of leaders builds extensive Gantt diagrams and communicates them to developers. Plans are task-based with little flexibility for changes since little deviations impact the project. Conversely, LPD plans accommodate the variability and unpredictability of development (OOSTERWAL, 2010). Subsystems plan their activities to achieve their goals based on the specificity of their reality. Goals are broken into small packages and distributed to deliver results at each IE.

IE are workshops with specific goals, inputs, and outputs, comprising all teams composing subsystems, CE, and others involved in the development process (MASCITELLI, 2011). Their main functions are to enable the verification of the progress made in delivering value and support decision-making regarding narrowing down DS regions (PESSOA; TRABASSO, 2017). The information in LPD is pulled and not pushed, enabling learning and reflection. IE serves as a pacemaker for pulling decisions, experiments, and learning. Furthermore, they stimulate concurrent engineering, uncovering problems, and knowledge creation. Planning is not centred on a group of leaders but is the responsibility of the teams that execute it (PESSOA; TRABASSO, 2017). Hence, the development flow in LPD follows RBM precepts.

IE are underpinned by real and unambiguous data, a structured agenda, and active leadership participation. They dictate the narrowing down of solution alternatives in the SBD process, i.e., they form the basis of the NDP (OOSTERWAL, 2010). Throughout LPD, development teams will achieve their goals by establishing well-defined deliveries accomplished by executing short cycles of PDCA, synchronously to the IE (PESSOA;

TRABASSO, 2017). LC are sets of PDCA cycles that occur between IE (LIKER; MORGAN, 2011; PESSOA; TRABASSO, 2017). They form a chain of small, cyclic, constant, and cadenced periods with experiments to acquire knowledge regarding the product (WARD, 2011). Since LC are based on the PDCA, the PDP becomes a problem-solving process seeking to move from a current design state to a state that meets the desired parameters (SÖRENSEN, 2006; SCHIPPER; SWETS, 2010).

The NDP eliminates solution alternatives assisted by tools, modelling, and experimentation (MAJERUS, 2016). Quick, value-oriented, and knowledge-building experimentation enables solving design problems in a structured and scientific manner. Furthermore, it supports learning to continually improve and reduce uncertainties throughout development (PESSOA; TRABASSO, 2017). LC assist in controlling risks in projects with many uncertainties (MAJERUS, 2016). A crucial element of LPD that supports SBD is rapid prototyping and the concept of 'test then design'.

In traditional PDP, first, the project is made and then tested. LPD opposes this idea, i.e., the solution is tested to check feasibility and performance before being considered (OOSTERWAL, 2010). Rather than conducting case-specific tests to answer project questions and simply meeting project demands, LPD seeks to conduct general tests to build knowledge. Unlike the traditional ‘design then test’ logic, LPD preconises the 'learn than design' thinking (OOSTERWAL, 2010).

The technique known as *ijiwara*, or failure testing, is an example of a test beyond design in LPD. It consists in pushing components, materials, or even subsystems to the limit, i.e., to the point of rupture or breakage. These tests or experiments enable engineers to build performance charts, named boundary curves, and verify the physical limits of subsystems (OOSTERWAL, 2010; PESSOA; TRABASSO, 2017; WARD, 2011). The integration prototype is also an important milestone in LPD projects. It is an experiment to verify the compatibility between subsystems and the achieved performance when integrated and working together (WARD, 2011).

Given the nature of SBD in considering DS and the global optimum, the most crucial tool associated with the NDP are the ToC. They assist in understanding the relationships between design parameters, storing information, and highlighting knowledge and technological gaps (LEVANDOWSKI; FORSLUND; JOHANESSON, 2013). Development teams generate ToC through prototyping and testing, studying different performance parameters (PESSOA; TRABASSO, 2017).

2.3. Principles and elements of the Set-Based Design

> *SBCE is not simply the parallel development of various solution alternatives to reduce project risk (...). SBCE is a carefully orchestrated development process that explores the principles of learning through experimentation cycles with the goal of understanding project risks by exploring their boundaries (OOSTERWAL, 2010).*

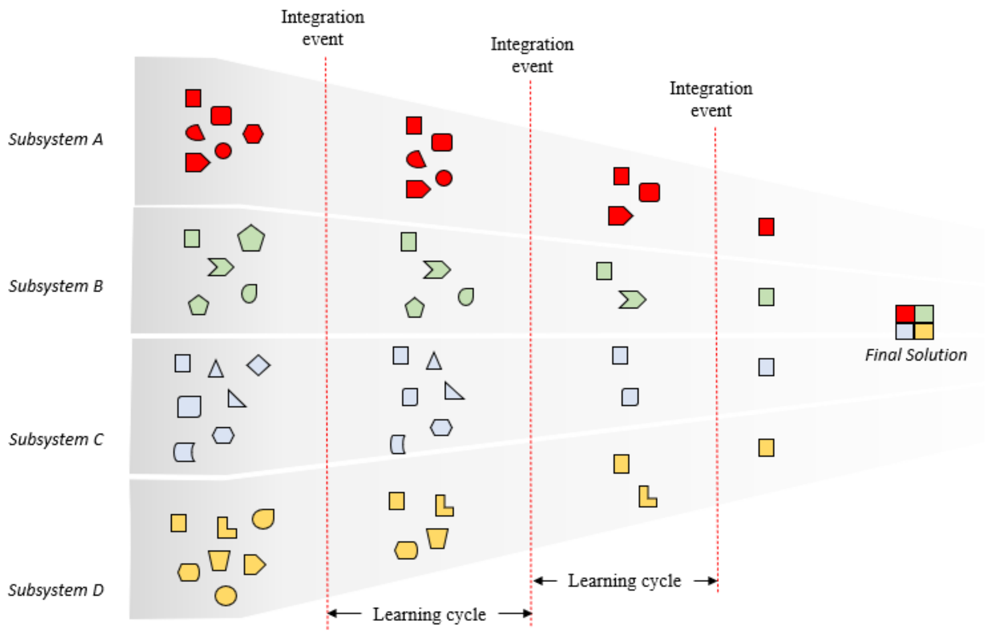
SBD focuses on using a set of design parameters to create knowledge. It is based on LC to build knowledge over time, defining what is already known and what needs to be learned (OOSTERWAL, 2010). Rather than choosing the best solution, SBD considers sets of alternatives and their elimination throughout the PDP (KERGA; TAISCH; TERZI, 2013; KERGA *et al.*, 2014). Knowledge is created in the early stages by varying parameters and analysing their behaviour to explore and understand the feasibility limits (OOSTERWAL, 2010).

Deploying the product into subsystems enables the concurrent design by teams from different functions associated with the product (WARD, 2011). Each subsystem explores its DS or sets of solution alternatives independently. They interact amongst them gradually, comparing the solution sets and looking for intersections. Thus, teams converge on a solution fully compatible with all subsystems (KERGA; TAISCH; TERZI, 2013; KERGA *et al.*, 2014).

The strategy of SBD is to remove unfeasible or uninteresting alternatives, consequently reducing the size of the set, as presented in Figure 2.3. "Rejecting the third worst solution rather than the worst is less critical when compared to the magnitude of failing if the third best alternative is chosen for development over the best" (RAUDBERGET, 2010b). In SBD, subsystems evaluate solutions by comparing design requirements, looking for intersections with other subsystems, and using rapid prototyping, testing, and ToC (QURESHI *et al.*, 2010).

Only when ToC are fully drawn and understood, there is sufficient available data, and potential problems with the most critical subsystems do not require the DS to remain flexible, the team discards alternatives (WARD, 2011). Visualising the knowledge produced and its gaps creates a technological landscape that directs development efforts for future products (OOSTERWAL, 2010). SBD principles are mapping the DS, integrating by intersection, and establishing feasibility before commitment (SOBEK II; WARD; LIKER, 1999).

Figure 2.3. Narrowing-down process



Source: Adapted from OLIVEIRA *et al.* (2018)

2.3.1 Mapping the design space

The DS is the space containing all possible values for the project parameters, i.e., all values that the variables that define the system or subsystem can assume (MORGAN; LIKER, 2006). At the very beginning of product development, the DS is unlimited. It is reduced as constraints are imposed. At the end of the design, the main result is a point in the DS representing the final product, i.e., the design parameters that define it. Thus, this principle indicates the importance for SBD to widely explore the DS to develop the best possible project (SÖRENSEN, 2006).

The first principle of SBD, also known as the exploration principle, consists of the exploration and mapping of the DS through the definition of sets of alternatives to feed the solution convergence process (KERGA; TAISCH; TERZI, 2013; KERGA *et al.*, 2014; SOBEK II; WARD; LIKER, 1999). Mapping the DS means defining the feasibility regions, i.e., where it is possible to design to meet requirements. Furthermore, once boundaries are delimited, an effort begins to discover where and how frontiers can be expanded, seeking innovation (KAO, 2006). Exploring the DS previously to the NDP avoids problems and assists in solution alternatives generation (MAJERUS, 2016).

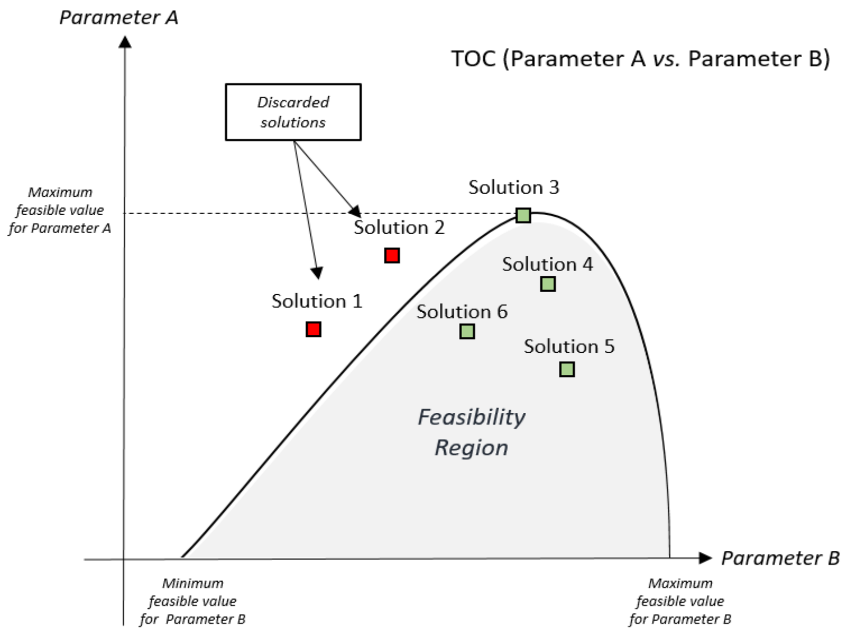
The techniques applied to the initial DS study are benchmarking, reverse engineering, research on available technologies, consulting stakeholders (manufacturing, marketing, sales, and others), computational forecasting, rapid experiments, and knowledge reuse (MAJERUS, 2016). Three elements underpin the principle of mapping DS: (1) the definition of feasibility regions, (2) the exploration of trade-offs through the design of multiple alternatives, and (3) the communication of sets of alternatives (SOBEK II; WARD; LIKER, 1999). Each subsystem must define its feasibility region independently and in parallel. Constraints are imposed based on CR, analysis, experimentation, testing, and information from the CE or specialists, such as production engineers (SOBEK II; WARD; LIKER, 1999).

Tools are applied to support the NDP, such as checklists built with prior knowledge, including standard dimensions, existing manufacturing, material limits, and limits associated with reliability (SOBEK II; WARD; LIKER, 1999). They enable the visualisation of knowledge and the definition of DS boundaries, which exposes development risks (OOSTERWAL, 2010). The exploration of trade-offs through the design of multiple alternatives dictates how SBD design, simulate, and build prototypes to learn about the considered solutions and to identify which ones should not remain in the process. Engineers build prototypes to establish, through testing and data collection, relationships between conflicting parameters whenever possible (SOBEK II; WARD; LIKER, 1999). Thus, the learning and experimentation process is grounded in ToC, which identifies design alternatives outside the feasibility regions during the NDP, as presented in Figure 2.4.

The principal element differentiating SBD from traditional product development approaches is the exploration of trade-offs. The logic in SBD is 'test then design' while other approaches use the 'design then test' principle. Initially, prototypes and generic simulations are performed to study the system's behaviour and create knowledge. It is a requirement for deciding which design alternative to eliminate. The third element behind the principle of mapping DS, communicating sets of alternatives, preconises the communication of feasibility regions and sets rather than one idea at a time.

Visualising the DS instead of just one point clears the consequences of making one decision rather than another (SOBEK II; WARD; LIKER, 1999). The idea is to focus on the global rather than the local optimal. A solution that may be optimal for a subsystem can degrade overall performance. When one subsystem proposes only its best idea, it does not allow others to see all the possibilities (SOBEK II; WARD; LIKER, 1999).

Figure 2.4. The ToC and the DS representation

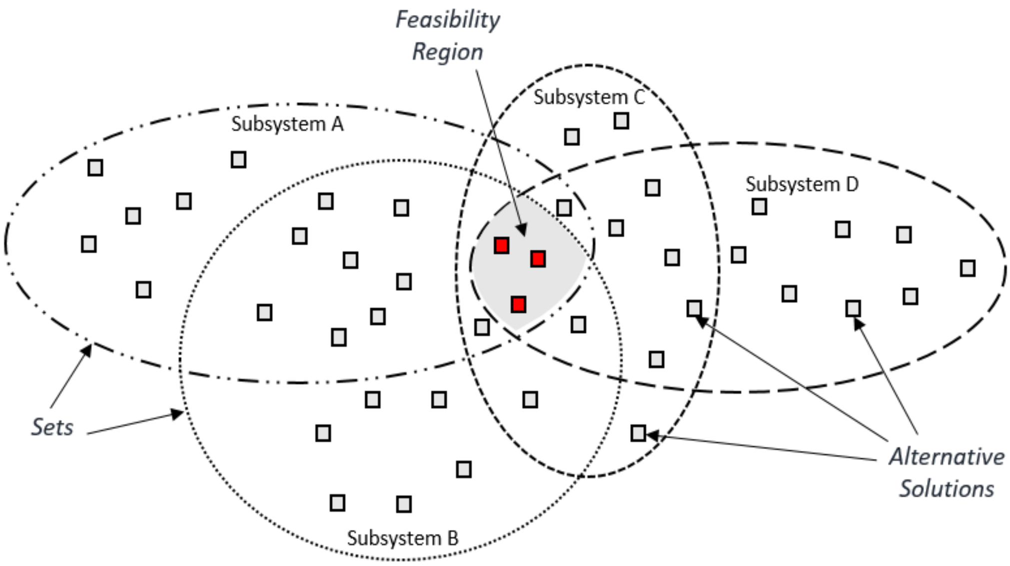


2.3.2 *Integrate by intersection*

The principle governing the NDP is integrating by intersection. The logic behind this principle is that there is no point in considering a solution incompatible with all subsystems. Therefore, the acceptable design solution must be at the intersection of the DS of all subsystems, as shown in Figure 2.5. This principle is also known as the compatibility principle because it focuses on system compatibility before finalising individual projects (MORGAN; LIKER, 2006). Three fundamental elements constitute the principle of integrating by intersection: (1) seeking the intersection of viable sets, (2) imposing minimum constraints, and (3) seeking conceptual robustness (SOBEK II; WARD; LIKER, 1999).

Subsystems seek intersections in the DS, i.e., which alternatives are suitable or incompatible with the ones of other subsystems. When incompatibility arises, solutions are discarded from the process. This element is crucial for system optimisation (KERGA; TAISCH; TERZI, 2013; KERGA *et al*., 2014). The imposition of minimum constraints means keeping options open, i.e., consider the largest DS for as long as possible. It leads to a more robust design and enhances value-added (MAJERUS, 2016). In an SBD environment, one should seek to impose minimum constraints to ensure flexibility, exploit DS as much as possible, and make adjustments that improve integration between subsystems (SOBEK II; WARD; LIKER, 1999).

Figure 2.5 - Integrate by intersection



Source: Adapted from Alessandria *et al*. (2017)

Product development begins with large DS. This space is restricted, and the possibilities decrease as decisions are made. Simultaneously, the cost of change decisions increases. Thus, the convergence process must be orchestrated to ensure that the DS is not constrained too quickly (MAJERUS, 2016). The main implication of SBD of imposing minimum restrictions is that specifications and communication are based on value ranges rather than specific values (KERGA; TAISCH; TERZI, 2013; KERGA *et al.*, 2014). The third element, seeking conceptual robustness, is making robust design decisions that remain valid even in the face of other choices by different engineers in further stages of the process (KERGA; TAISCH; TERZI, 2013; KERGA *et al.*, 2014). It implies designing a subsystem that works independently of what other subsystems design (SOBEK II; WARD; LIKER, 1999).

2.3.3 Establish feasibility before commitment

The third principle comprises gradually narrowing down the alternatives rather than choosing only one. Three elements are associated with the principle of establishing feasibility before commitment: (1) narrow down the sets of alternatives gradually while increasing the level of detail, (2) remain within the DS once committed, and (3) control development by managing the uncertainties at the gates of the development process (SOBEK II; WARD; LIKER, 1999). SBD is a decision process that gradually eliminates design alternatives until only one remains (SOBEK II; WARD; LIKER, 1999). The longer it takes for deciding, the more knowledge is available to support it. It implies lower risks associated with product development. Furthermore, this postponement enables knowing the latest state of the market and available technologies (MAJERUS, 2016).

Engineers increase the detail and the level of maturity of the alternatives as sets are reduced. Before committing to a particular concept, developers must ensure that it is feasible. The goal is to avoid problems and unforeseen events in the upcoming stages of development (KERGA; TAISCH; TERZI, 2013). Based on this, it is possible to establish feasibility before commitment. Furthermore, narrowing the sets of alternatives gradually while increasing the level of detail enables this principle to be achieved (SOBEK II; WARD; LIKER, 1999). The second element, remaining in the set once committed, is crucial for the reliability of the NDP. The value of set communication is compromised if a subsystem considers a solution in discordance with others (SOBEK II; WARD; LIKER, 1999).

IE not only enable the narrowing down of solutions but the agreement about the current DS. Deleting ideas in stages favours considering different alternatives and provides time to influence the NDP of other subsystems. Thus, the third and last element consists of using the IE to control the NDP and its uncertainties to integrate and intersect the DS (SOBEK II; WARD; LIKER, 1999).

2.4. STATE-OF-THE-ART MODELS AND FRAMEWORKS FOR THE SET-BASED DESIGN

In order to accomplish the objectives of this Doctoral Dissertation, it was necessary to perform a systematic review of SBD to explicitly, transparently, reliably, and thoroughly assess the literature pertaining to this field of study in a reproducible manner. The systematic review enabled to map state-of-the-art models and frameworks for the SBD, grounding the development of the proposed model. The SBR was undertaken following the roadmap proposed by Conforto, Amaral, and Silva (2011). The authors presented an SBR roadmap, named RBS Roadmap, developed for state-of-the-art mapping in the operations management field. This section presents the steps and results obtained by applying this procedure.

2.4.1 Systematic bibliographic review

The review commenced with the definition of the review problem and objectives. According to Conforto, Amaral, and Silva (2011), the review problem is an unambiguous, clear, precise, and possible-to-solve question. Thus, 'What are the models and frameworks for the SBD existing in the literature?' was defined as the review problem guiding the research. The objective was to identify all models and frameworks related to the SBD. The primary source of research was selected through an initial exploratory search in web search engines, which comprises the third step of the SBR methodology.

As this work pertains to engineering science and the related cognitive and social sciences, the research databases selected for the data extraction were Scopus®, Engineering Village (Compendex® from Elsevier), Emerald® for engineering research publications, and Web of Science (Thomson Reuters) cover the broader landscape of sciences relating to design as a cognitive and social science. The database Proquest (ABI Inform) was included to expand search depth since it contains dissertations and other institutional publications.

SBD is a concept intrinsically related to LPD. As identified in the exploratory research, models and frameworks developed for LPD also contain insights and elements of SBD, which pertain to the SBR goals. Thus, keywords that comprise LPD were added to the query. Therefore, the combination of keywords selected to query the research databases 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")). Carrying forward the research, inclusion and exclusion criteria for publications were defined:

1 Works containing keywords selected to query in the title, abstract, or keywords;
2 Articles, reviews, book chapters, dissertations, or thesis;
3 Documents in English;
4 Works with provided full-text access;
5 Publications centred on SBD or LPD presenting a model or framework with inputs, outputs, or the NDP.

The review process consisted in excluding publications that did not meet inclusion criteria. The pool of publications was extracted from the target research databases by applying the defined query. The review continued with the seventh and eighth steps comprising the definition of methods and tools and the review planning. The tool selected to assist in the SBR was a bibliographic manager to organise and filter results. After filtering, the models and frameworks were organised into a spreadsheet following a template of relevant fields/columns comprising the authors, year of publication, source (name of the journal or conference proceedings), type of document (article or proceedings paper), title, classification (before, after or during the NDP) and highlights of the model/framework.

The filtering method was performed according to Conforto, Amaral, and Silva (2011). First, duplicated references were eliminated in the bibliographic manager. Then, publications were extracted based on their title and abstract content, followed by their introduction and conclusion, focusing on finding publications that did not present models or frameworks pertaining to this study. Finally, the last filter was applied by reading the full text. Given the necessity of performing careful filtration, two premises guided the process: (1) Works that gave rise to doubts were kept being reassessed in the next stage, and (2) When the title and abstract did not provide enough information, the full text was scanned.

The extraction resulted in a total of 13012 publications. After the filtering process, 121 works remained, comprising all models and frameworks for SBD found in the literature (Fig. 2.6). The publications were classified through examination and assessment of their content assisted by the previously mentioned spreadsheet. A synthesis of all subjects and findings was registered and refined to report on the findings, recommendations, and future research directions.

The publications found were categorised regarding presenting inputs, outputs, or the NDP (Appendix A). Two years can be highlighted by observing the temporal distribution of the 121 publications (Fig. 2.6). The first model/framework was published in 1992, although publications in LPD have been produced since 1987 (TOCHE, 2017). Furthermore, the year 2010 is when the topic became more widely addressed. The leading publishers in SBD are the journal 'Concurrent Engineering: Research and Applications' and the 'International Conference on Engineering Design (ICED)', as presented in Table

2.1. The publications are reported in 35 scientific journals and 31 international conferences, not discriminating by year.

Figure 2.6. Systematic bibliographic review results

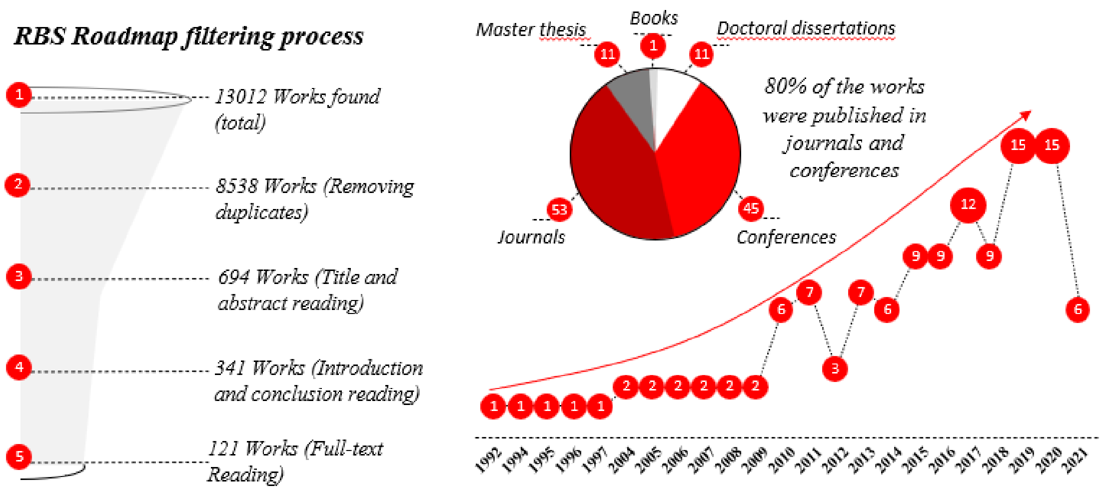


Table 2.1. Journals and conferences with most publications

Type	Title	Publications
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	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

Source: Oliveira *et al.* (2022a)

The keywords most present in publications are related to the root words ‘set-based’, ‘design’, ‘product’, and ‘lean’., as presented in Table 2.2. It indicates the necessity of including these keywords in the query when researching this field.

Table 2.2. Keywords mapping

Root	Main variations	Appearances
Set-based	Set-based design or SBD, set-based concurrent engineering or SBCE, set-based conceptual design, and set-based measures	77
Design	Design method, methodology, theory, process, decisions, intention, evaluation, engineering, structural, collaborative, organisation, conceptual, process, early design stages or phases, value driven design, design preference, simulation-based design, design structure matrix, design method verification, parametric design, multi objective design, and design for X variations	54
Product(s)	Product architecture, development, development process and projects, new * development, lifecycle management, modelling/models, innovative product development, concurrent product-production reconfiguration, agile product development, sustainable products, and platform products	34
Lean	Lean development, lean product development, lean product and process development, lean systems engineering, lean transformation, lean design, lean PPD, lean thinking, lean philosophy, and lean practices	33
System(s)	Systems engineering, architecture, production system, engineered resilient systems, mechatronic systems, and model-based systems engineering	23
Knowledge	Knowledge life cycle, knowledge-based engineering, knowledge-based environment, knowledge management, knowledge provision, knowledge shelf, knowledge visualisation, knowledge reuse, knowledge creation and visualisation, visual knowledge, and creating knowledge	20
Contradictions or trade-offs	Trade-off curves or ToC, contradiction analysis	18
Modelling	Cost modelling, functional modelling, dynamic platform modelling, dependency and structure modelling, and function-means modelling	13
Decision	Decision analysis and decision-making	8
Tradespace or DS	Tradespace exploration and DS exploration	7
Manufacturing	Manufacturing uncertainties, manufacturing planning, manufacturing process planning, and manufacturing platform	4

Furthermore, it demonstrates the suitability of the selected keywords in this research. The literature analysis evidenced the growing interest in SBD from the most different field research areas and applications, as presented in Table 2.3. SBD is not addressed broadly since no model simultaneously approaches inputs, outputs, and the NDP. Publications focus on methods and techniques for early development stages. Few methods and techniques presented an integrated approach with the NDP. Furthermore, crucial aspects such as the IE, the use of ToC, and the LC have not been sufficiently clarified in the literature.

Table 2.3. Themes approached by publications

Themes	**Authors**
ToC and DS representation	Araci, Al-Ashaab, and Maksimovic (2015), Araci, Al-Ashaab, and Maksimovic (2016a), Araci *et al.* (2016b), Araci *et al.* (2017), Araci *et al.* (2020), Araci, Al-Ashaab, and Almeida (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, Abdulateef, and Al-Ashaab (2020), Nahm and Ishikawa (2005), Ortiz (2021), Parker *et al.* (2017), Rosen (2015), Sasaki and Ishikawa (2015)
Models for planning	Chen *et al.* (2020), Diels, Rudolf, and Schuh (2015), Kerga, Khan, and Arias (2012a), Kerga, Taisch, and Terzi (2012b), Lu *et al.* (2020), Martínez (2010), Pessoa, Loureiro, and Alves (2007), Schuh, Rudolf, and Luedtke (2016), Zhong and Dockweiler (2020)
Selection and analysis of alternatives	Avigad and Moshaiov (2009), Blindheim *et al.* (2020), Buchanan *et al.* (2019), Kim (2015), Malak Jr. (2008), Pillai *et al.* (2020a), Pillai *et al.* (2020b), Stolt *et al.* (2017), Wasim (2012), Wasim *et al.* (2013)
General SBD models	Ammar *et al.* (2019a), Bernstein (1998), Chan (2016), Frye (2010), Georgiades *et al.* (2019), Kerga, Taisch, and Terzi (2013), Kerga *et al.* (2014), Khan *et al.* (2011), Mascitelli (2011), Maulana *et al.* (2017), Mckenney, Kemink, and Singer (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), Shallcross, Parnell, and Pohl. (2020b), Shallcross *et al.* (2021a), Shallcross *et al.* (2021b), Shallcross *et al.* (2021c), Strom, Raudberget, and Gustafssom (2016a), Strom, Raudberget, and Gustafssom (2016b), Wade (2018), Ward *et al.* (1995)
Early-stage models	Al-Ashaab *et al.* (2013), Amine, Pailhès, and Perry (2017), Bertoni and Bertoni (2019), Kennedy, Sobek II, and Kennedy (2014), Parnell *et al.* (2019), Santos *et al.* (2020), Schäfer and Sorensen (2010), Schulze (2016), Small (2018), Specking *et al.* (2018a), Toshon *et al.* (2017)
Models for specific environments	Ammar *et al.* (2017), Ammar *et al.* (2018), Ammar *et al.* (2019b), Ammar *et al.* (2019c), Amine, Perry, and Pailhès (2016), Borchani *et al.* (2018), Borchani *et al.* (2019), Johanesson *et al.* (2017), Landahl *et al.* (2020), Lee (1996), Levandowski, Raudberget, and Johanesson (2014a), Levandowski, Michaelis, and Johannesson (2014b), Müller, Panarotto, and Isaksson (2019), Raudberget, Michaelis, and Johanesson (2014), Raudberget (2015), Raudberget *et al.* (2015)
Implement SBD	Autzen (2013), Raudberget (2011)
Knowledge and reasoning models	Furian *et al.* (2011), Maksimovic (2013), Raudberget (2010a), Raudberget (2010b), Suwanda, Al-Ashaab, and Beg (2020), Whitcomb and Hernandez (2019)
SBD and different techniques	Bhushan (2007), Essamlali, Sekhari, and Bouras (2017), Fernández (2005), Ishikawa and Sasaki (2020), Kao (2006), Lermen *et al.* (2018), Saad, Rotzer, and Zimmermann (2019), Souza and Borsato (2015)

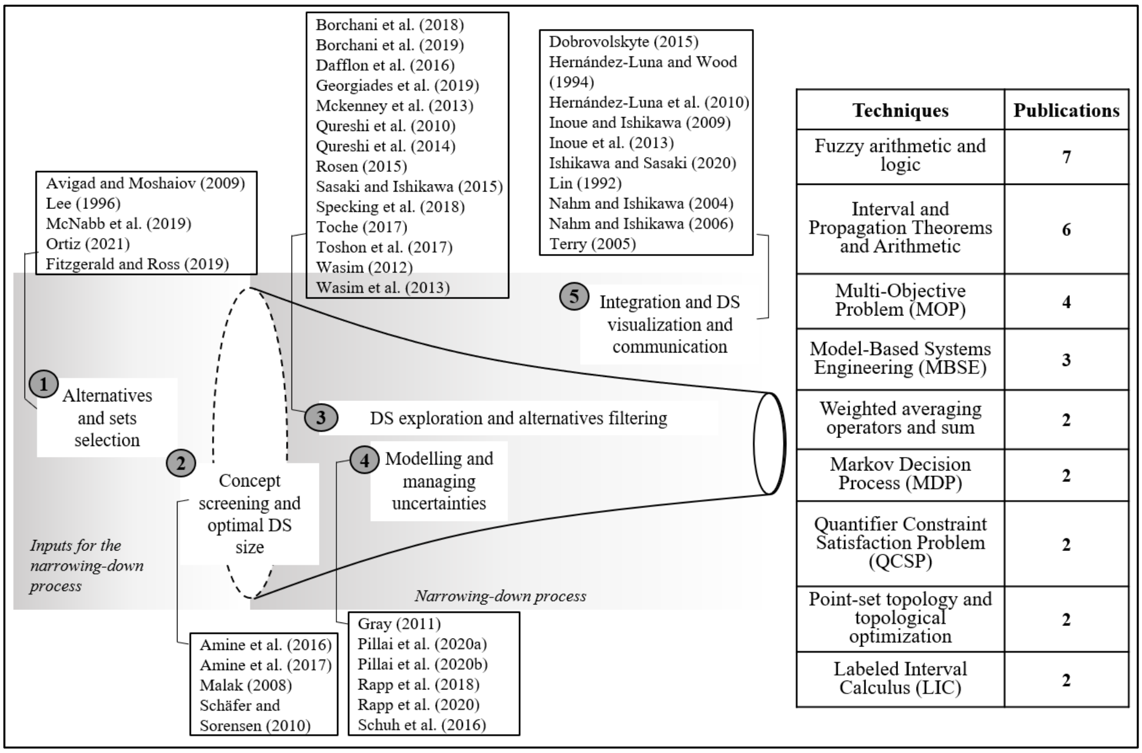
Computer tools to support SBD	Dafflon *et al.* (2016), Dobrovolskyte (2015), Fitzgerald and Ross (2019), Jonkers and Shahroudi (2020), Qureshi *et al.* (2014), Rapp *et al.* (2018), Rapp, Witus, and Kalgave (2020), Shallcross *et al.* (2021b), Shallcross *et al.* (2021c), Stumpf *et al.* (2020), Terry (2005), Toche (2017)

Source: Oliveira *et al*. (2022a)

Procedural works for assisting in concepts and tools application were proposed, but a question remains regarding their connection with the narrowing down of alternatives. No studies addressed the outputs of SBD, i.e., models for assisting in closing the NDP when only one solution or a sufficiently small region of the DS remains.

Most of the models propose activities and supporting tools. Some research areas and applications receive considerable focus, such as platform projects and complex systems, mentioned by 13% of the publications. Furthermore, albeit insipiently, ToC have been gaining space among models over the years. The support from computational and quantitative tools in mapping and analysing the DS is a way out of dealing with the complexity and the massive amount of data generated in SBD. It is also a considerable concern in literature with 40 publications, as presented in Figure 2.7.

Figure 2.7. Computational and quantitative models for SBD



Source: Oliveira *et al*. (2022a)

Efforts to gather SBD with other consolidated techniques and principles were found in the literature, such as TRIZ (BUSHAN, 2007), sustainability (LERMEN *et al*., 2018), agile (SAAD; ROTZER; ZIMMERMANN, 2019), scrum (FERNÁNDEZ, 2005), and Product Lifecycle Management (PLM) (ESSAMLALI; SEKHARI; BOURAS, 2017). Furthermore, the literature approaches the transformation from a consolidated PDP to LPD (AUTZEN, 2013; RAUDBERGET, 2011). Concerning inputs, outputs, and the NDP, from the 121 models and frameworks found, 82 approach inputs for the NDP and 97 present supporting tools and steps for narrowing-down alternatives.

2.4.2 Inputs for the narrowing-down process

The literature focuses on the early stages and activities of SBD. Among the inputs mentioned for the NDP stand out the value research and definition, value deployment for the several levels of the system, planning for SBD, DS mapping and representation, and Concept Screening (CS). Furthermore, activities to prepare for the NDP are approached, as shown in Table 2.4. Value research and definition are considered fundamental for the SBD and one of its first steps. DS reduction is possible only with the value deeply understood and spread among developers (AL-ASHAAB *et al*., 2013; AUTZEN, 2013; KHAN *et al*., 2011; LERMEN *et al*., 2018; MAULANA *et al*., 2017; TOSHON *et al*., 2017).

The development follows by identifying the subsystems of the product and deploying the value for its levels and teams (AMMAR *et al*., 2017; AMMAR, 2019a; AMMAR *et al*. 2019b; AMMAR *et al*. 2019c; AUTZEN, 2013; BORCHANI *et al*., 2019; DOBROVOLSKYTE, 2015; FERNÁNDEZ, 2005; JOHANESSON *et al*., 2017; KERGA; KHAN; ARIAS, 2012a; KERGA; TAISCH; TERZI, 2012b; KERGA; TAISCH; TERZI, 2013; KHAN *et al*., 2011; LANDAHL *et al*., 2020; LERMEN *et al*., 2018; LEVANDOWSKI; RAUDBERGET; JOHANESSON, 2014a; LEVANDOWSKI; MICHAELIS; JOHANNESSON, 2014b; MASCITELLI, 2011; MEBANE *et al*., 2011; MÜLLER; PANAROTTO; ISAKSSON, 2019; OLIVEIRA, 2017; OLIVEIRA *et al*., 2017; OLIVEIRA *et al.* 2018; RAUDBERGET *et al*., 2015; RAUDBERGET, 2015; SCHUH; RUDOLF; LUEDTKE, 2016; SIISKONEN, 2019).

Some authors suggest the use of the QFD and functional flow diagrams to define what are the subsystems related to the product, perform value deployment of the system to the level of subsystems and components and also, to analyse the interaction between functions (AL-ASHAAB *et al*., 2013; ESSAMLALI; SEKHARI; BOURAS, 2017; KAO, 2006; KERGA *et al*., 2014; LERMEN *et al*., 2018; OLIVEIRA, 2017; TOSHON *et al*., 2017). Furthermore, QFD can be used to assist in product planning, assembly/part deployment, production planning, and planning for process control (KAO, 2006).

Table 2.4. Main early-stages activities among publications

Activities	**Authors**
Market studies and customer research	Al-Ashaab *et al*. (2013), Ammar *et al*. (2019b), Ammar *et al*. (2019c), Araci *et al*. (2017), Autzen (2013), Borchani *et al*. (2019), Lermen *et al*. (2018), Maulana *et al.* (2017), Santos et al. (2020)
Definition of requirements of customers and stakeholders	Al-Ashaab *et al*. (2013), Autzen (2013), Borchani *et al*. (2019), Essamlali, Sekhari, and Bouras (2017), Kao (2006), Kerga *et al.* (2014), Lermen *et al*. (2018), Toshon *et al*. (2017)
Identify TRL for each solution	Al-Ashaab *et al*. (2013), McNabb *et al*. (2019), Schulze (2016)
Classify the Level of Innovation (LI) intended for the product	Al-Ashaab *et al*. (2013), Ammar *et al*. (2018), Autzen (2013), Khan *et al*. (2011), Maulana *et al.* (2017), Schulze (2016)
Determine targets and goals for the product	Al-Ashaab *et al*. (2013), Autzen (2013), Essamlali, Sekhari, and Bouras (2017), Khan *et al*. (2011), Parnell *et al*. (2019), Parker (2017), Small (2018), Specking *et al*. (2018a)
Align the product with the product development or company strategy	Al-Ashaab *et al*. (2013), Autzen (2013), Khan *et al*. (2011), Lermen *et al*. (2018), Parker (2017), Parnell *et al*. (2019), Small (2018), Specking *et al*. (2018a)
Identify product attributes and define subsystems and teams	Autzen (2013), Lermen *et al*. (2018), Lu *et al.* (2020), Toshon *et al*. (2017)
Analyse interactions between subsystems	Autzen (2013), Kao (2006), Kerga *et al.* (2014)
Product architecture, functionality, and concept definition	Al-Ashaab *et al*. (2013), Autzen (2013), Borchani *et al*. (2019), Khan *et al*. (2011), Lermen *et al*. (2018), Parker (2017)
Extract design concepts from previous projects	Chan (2016), Khan *et al.* (2011), Toshon *et al*. (2017)
Map the DS by defining variable, options and factors ranges	Ammar *et al.* (2019a), Bernstein (1998), Borchani *et al*. (2019), Frye (2010), Hernández-Luna and Wood (1994), Mckenney, Kemink, and Singer (2011), Mebane *et al.* (2011), Ortiz (2021), Raudberget (2010a), Raudberget (2010b)

Two approaches can be highlighted regarding team assignment and the organisational structure necessary to apply SBD. One is to assign a team for each subsystem or to have a team working at the system level (SCHULZE, 2016). Another is an integration team to synchronise and control activities of the subsystems without knowledge trading between them (MCKENNEY, 2011). The size of the initial DS at the beginning of the NDP will dictate the resources needed during the development. Thus, it is not feasible to consider the DS thoroughly. Resource restrictions lead to a need to reduce the DS early while keeping development risks lower (LEE, 1996).

The initial DS bounding is an early-stage activity performed based on previous projects and knowledge, resources available to develop, and competing products (AL-ASHAAB *et al*., 2013; BHUSHAN, 2007; FURIAN *et al*., 2011; KHAN *et al*., 2011; MAKSIMOVIC, 2013; SCHÄFER; SORENSEN, 2010). Furthermore, establishing initial key parameters and ranges for study, assessing products from competitors, and identifying and prioritising systems contradictions or trade-offs are mentioned as steps for the NDP (SCHAFER; SORENSEN, 2010; MEBANE, 2011; KERGA; TAISCH; TERZI, 2013; KERGA *et al*., 2014; OLIVEIRA, 2017; PARKER, 2017). A hindering factor for SBD adoption is the considerable effort and resources required to execute the NDP.

Two techniques were proposed to balance available resources with the size of the DS. The first is to define the innovation level of each subsystem to decide the DS size, leading to the possibility of a hybrid approach with PBD and SBD simultaneously (AL-ASHAAB *et al*., 2013; AMMAR *et al*. 2018; AUTZEN, 2013; KHAN *et al*., 2011; MAULANA *et al*., 2017; PESSOA; LOUREIRO; ALVES, 2007). The second is to identify in the DS regions with the highest chance of success to focus development efforts through a process named CS (AL-ASHAAB *et al*., 2013; AMINE; PAILHÈS; PERRY, 2017; AUTZEN, 2013; AVIGAD; MOSHAIOV, 2009; BERTONI; BERTONI, 2019; CHAN, 2016; DOBROVOLSKYTE 2015; ESSAMLALI; SEKHARI; BOURAS, 2017; FERNÁNDEZ, 2005; LEE, 1996; MAULANA *et al*., 2017; MÜLLER; PANAROTTO; ISAKSSON, 2019; PARKER *et al*., 2017; RAUDBERGET, 2011; SCHÄFER; SORENSEN, 2010; SCHUH; RUDOLF; LUEDTKE, 2016; SCHULZE, 2016; TOCHE, 2017).

Methods were developed to support decision-making regarding the development strategy, such as the convergence-uncertainty-portfolio (SCHUH; RUDOLF; LUEDTKE, 2016) and the analysis of the performance analysis, Technology Readiness Level (TRL) analysis, and evaluation against uncertainty (AL-ASHAAB *et al*., 2013; AMINE; PERRY; PAILHÈS, 2016; MASCITELLI, 2011; SCHUH; RUDOLF; LUEDTKE, 2016).

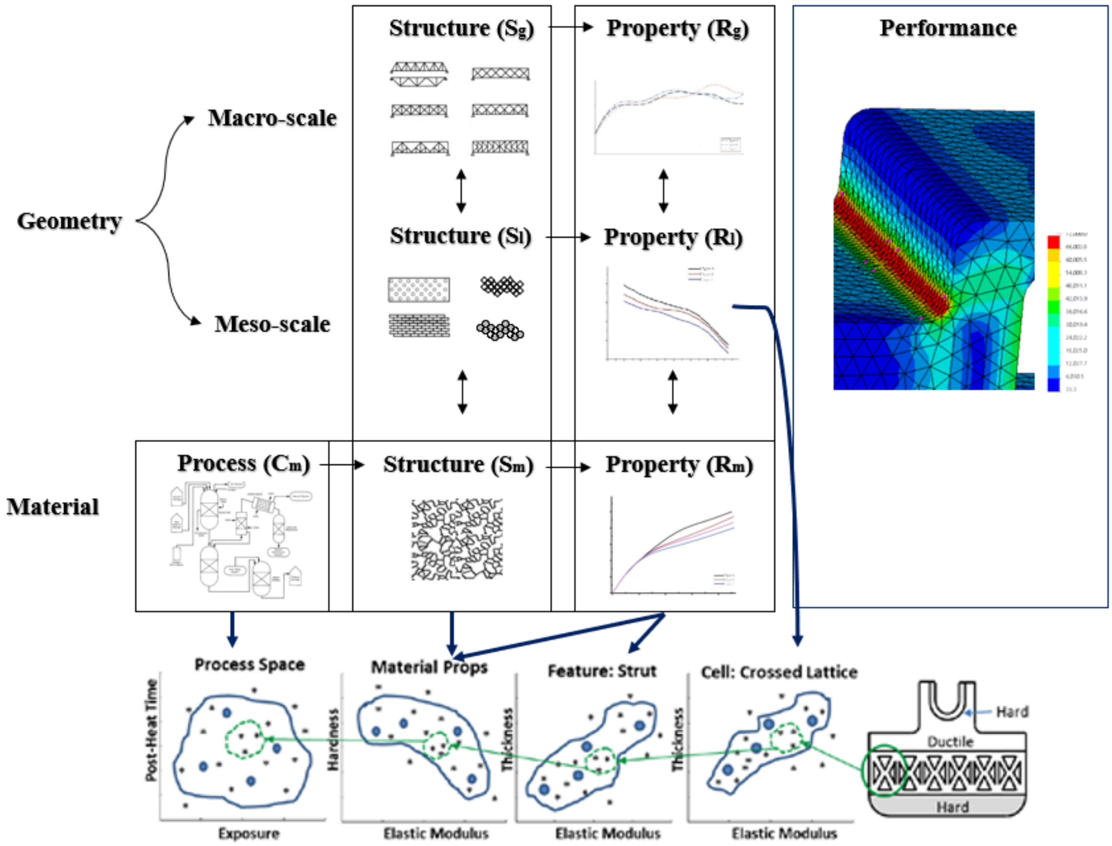
The DS mapping means defining the scope of the product along with its feasible regions and available options (AL-ASHAAB *et al*., 2013; AUTZEN, 2013; KHAN *et al*., 2011). It occurs after the establishment of subsystems and their specific targets. Based on that, it is possible to define feasible regions through current and previous knowledge analysis against constraints and targets (BHUSHAN, 2007; KHAN *et al.*, 2011). Methods to represent the DS to support the decision-making during the development are widely approached in the literature. Inclusively, the first publications in SBD are related to sets representation. They proposed methods for parameter design based on the Labelled Interval Calculus (LIC) technique to search for feasibility areas in the DS (LIN, 1992, HERNÁNDEZ-LUNA; WOOD, 1994).

Many authors proposed methods for the DS representation (HERNÁNDEZ-LUNA; MORENO-GRANDAS; WOOD, 2010; INOUE; ISHIKAWA, 2009; INOUE *et al*., 2013; NAHM; ISHIKAWA, 2005; NAHM; ISHIKAWA, 2006; RAUDBERGET, 2011; ROSEN, 2015; SASAKI; ISHIKAWA, 2015; ISHIKAWA; SASAKI, 2020; TOCHE, 2017). Their common ground is the necessity to communicate the current DS with a set representation method and inform where the preferable solutions are. Depending on the development goals, some regions of the DS are more desirable than others (HERNÁNDEZ-LUNA; WOOD, 1994, INOUE *et al*., 2013; MCKENNEY; KEMINK; SINGER, 2011; NAHM; ISHIKAWA, 2005, NAHM; ISHIKAWA, 2006; SASAKI; ISHIKAWA, 2015).

Among sets representation methods, the 'Preference Set-based Design' consists of four steps: set representation, propagation, modification, and narrowing (INOUE; ISHIKAWA, 2009; INOUE; ISHIKAWA, 2013; NAHM; ISHIKAWA, 2005; SASAKI; ISHIKAWA, 2015). The main objective is to combine the possible and the required performance space. Feasible areas are at the intersection between them. Furthermore, depending on the project emphasis, the most proper region can change for the same allowable interval. Other methods for DS representation are the extended morphological matrix (RAUDBERGET, 2011), uncertainty modelling (GRAY, 2011), and the multi-domain views in engineering design, presenting different abstraction levels related to the product (ROSEN, 2015; TOCHE, 2017).

The multi-scale process-structure-property relationship is explored by identifying a path through the design process hierarchy, as presented in Figure 2.8 (ROSEN, 2015). Many authors approached sets representation with the Enhanced Function-Means (E-FM) modelling to support the visualisation of technological/physical domains relations 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; RAUDBERGET; JOHANESSON, 2014a; LEVANDOWSKI; MICHAELIS; JOHANNESSON, 2014b; RAUDBERGET; MICHAELIS; JOHANESSON, 2014; RAUDBERGET *et al.*, 2015; RAUDBERGET, 2015; TOCHE, 2017). Furthermore, methods that connect EF-M to geometric features (MÜLLER; PANAROTTO; ISAKSSON, 2019) and production systems analysis to support changing bandwidths of platforms were developed (LANDAHL *et al.*, 2020; LEVANDOWSKI; MICHAELIS; JOHANNESSON, 2014b).

Figure 2.8. Multiscale process-structure-property relationships and back propagation of the DS



Source: Adapted from Rosen (2015)

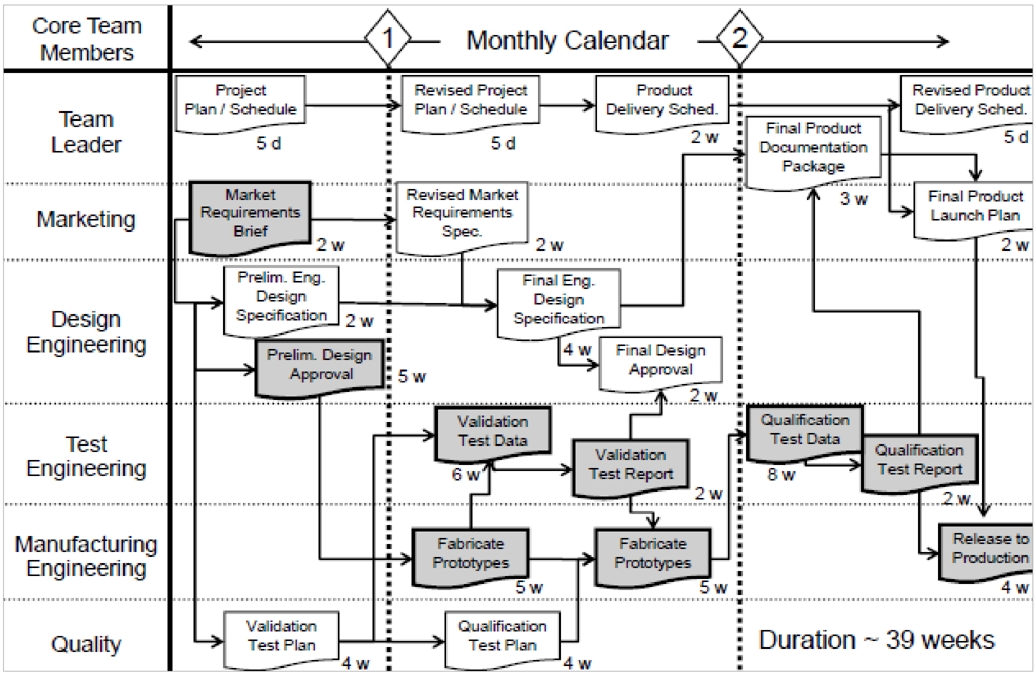
The most notorious tool associated with SBD and DS mapping are the ToC, cited by many authors (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al.*, 2016b; ARACI *et al.*, 2017; ARACI *et al.*, 2020; ARACI; AL-ASHAAB; ALMEIDA, 2021; MAULANA *et al.*, 2017; MAKSIMOVIC, 2013; MOHSIN; ABDULATEEF; AL-ASHAAB, 2020). Models were proposed for their generation (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI *et al*., 2020). Furthermore, works demonstrated the process of identifying the project trade-offs in the roof of QFD matrices, where the relations between technical engineering requirements are determined (KERGA *et al*., 2014; OLIVEIRA, 2017). ToC are classified into knowledge-based ToC, physics-based ToC, and math-based ToC (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI *et al*., 2020; ARACI *et al*., 2021).

The knowledge-based ToC are generated based on facts and information obtained from material providers, previous projects, and experiments. The physics-based ToC are drawn based on the fundamental physical characteristics and mechanisms of the product. Finally, the Math-based ToC are generated based on simulating engineering applications by mathematical modelling. Another classification is the causal and root contradiction. The causal contradictions are improved or solved by solving other contradictions, named 'root contradictions' (KERGA *et al*. 2014).

Regarding identifying and prioritising contradictions, the literature suggests the analysis of the roof of QFD matrices (KERGA *et al*., 2014; OLIVEIRA, 2017; OLIVEIRA *et al*., 2018) and contradictions classification (KERGA *et al*., 2014). Applications of tridimensional ToC were found (AMMAR *et al*., 2018; ARACI *et al*., 2020). The identification of design trade-offs, the process of generating ToC, and the analysis of concepts are the most explored in the ToC literature. Nevertheless, their use in IE and LC remains a gap. Furthermore, there is no consensus regarding the moment curves are drawn and studied.

Another input for the NDP is activities planning (AUTZEN, 2013; DIELS; RUDOLF; SCHUH, 2015; FRYE, 2010; LERMEN *et al*., 2018; MARTÍNEZ, 2010; MASCITELLI, 2011; OLIVEIRA, 2017; PESSOA; LOUREIRO; ALVES, 2007; SCHULZE, 2016). First, each integration event objective is established based on development goals. Then, the activities and deliverables of the LC are planned (PESSOA; LOUREIRO; ALVES, 2007). The idea is to distribute the work in small packages (sprints) for each subsystem, deployed from milestones and deliveries. Its result presents a delivery possible to be evaluated by customers (DIELS; RUDOLF; SCHUH, 2015). The Deliverable Roadmap (DR) was proposed as a planning tool for RBM (MASCITELLI, 2011; OLIVEIRA, 2017). It consists of a panel where the deliverables, IE, and milestones planned are registered (Fig. 2.9). The concept of gates is introduced by establishing quality gate (AUTZEN, 2013; SOUZA; BORSATO, 2015).

Figure 2.9. Deliverable Roadmap



Source: Mascitelli (2011)

Regarding team preparation and setting, it is necessary the establishment of teams not only at the subsystem level but also at the system level. The reason is to dictate targets for coupled parameters that will attend to system constraints and evaluate sets of solutions from all subsystems. In an iterative structure, the system-level team could control the NDP (MADHAVAN *et al*., 2009). Furthermore, efforts were made to integrate manufacturing evaluation to narrow down alternatives (AMMAR *et al*., 2018; BORCHANI *et al*., 2019; KERGA; TAISCH; TERZI, 2012b; KIM, 2015; LANDAHL, *et al*. 2020; LERMEN *et al*., 2018; LEVANDOWSKI; MICHAELIS; JOHANNESSON, 2014b; STOLT *et al*., 2017; SIISKONEN, 2019; WASIM, 2012; WASIM *et al*., 2013).

An innovative contribution was a cost modelling system with poka-yoke rules assessing geometric features of solutions and comparing them with proposed materials and machine availability. The goal is to find unfeasible alternatives or problems by performing a manufacturability assessment (WASIM, 2012; WASIM *et al*., 2013). Another innovative perspective considering manufacturing in SBD is a filtering technique focused on manufacturing resources. The idea is to indicate which processes and available equipment can manufacture each solution alternative. Solutions are considered for elimination when they are non-manufacturable, i.e., the fabrication processes in the site are not suitable (KIM, 2015).

Computational tools and methods were proposed in the literature (AMINE; PERRY; PAILHÈS, 2016; BHUSHAN, 2007; BORCHANI *et al*., 2018; DAFFLON *et al*., 2016; FERNÁNDEZ, 2005; FITZGERALD; ROSS, 2019; GEORGIADES *et al*., 2019; GRAY, 2011; FRYE, 2010; FURIAN *et al*., 2011; JONKERS; SHAHROUDI, 2020; MALAK Jr., 2008; MASCITELLI 2011; MCNABB *et al*., 2019; QURESHI *et al*., 2014; RAPP *et al*., 2018; RAPP; WITUS; KALGAVE, 2020; RAUDBERGET, 2011; ROSEN, 2015; SASAKI; ISHIKAWA 2015; STUMPF *et al*., 2020; TERRY, 2005; TOCHE, 2017; TOSHON *et al*., 2017; WASIM 2012; WASIM *et al*. 2013).

The literature discussed the PBD orientation of computer tools commonly used in the PDP. The reason is that they enable only visualising and working on one concept or design alternative at a time. A set-based interface was developed to provide an environment where the developer can manipulate and compare more than one solution simultaneously. It enables set management, generation, manipulation, and evaluation (TERRY, 2005). Furthermore, efforts were made to model partially defined system alternatives and forecast properties of their final implementation, which may operate on different physical principles and involve multiple trade-offs (MALAK Jr., 2008). Finally, the use of artificial intelligence for processing the massive volume of data generated in SBD of multi-attribute projects was proposed (FITZGERALD; ROSS, 2019).

2.4.3 The narrowing-down process

The NDP is not well characterised and defined in the literature, even though it is the core of SBD. An example is regarding the beginning of the process. Some authors consider that the NDP begins when knowledge gaps are closed, ToC are all drawn and studied, and all relations between parameters are set (MASCITELLI, 2011). Whereas other authors affirm that since the resources are limited when a product development starts, the NDP begins by performing an initial narrowing on the DS (AL-ASHAAB *et al*., 2013; AMINE; PERRY; PAILHÈS, 2016; ARACI *et al*., 2017; AUTZEN, 2013; KHAN *et al*., 2011; SCHUH; RUDOLF; LUEDTKE, 2016).

Regarding the nature of the process, some authors consider the NDP from a sequential perspective, in which the activities are presented in a sequence with inputs and outputs (ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI *et al*., 2020; ESSAMLALI; SEKHARI; BOURAS, 2017; LERMEN *et al*., 2018). Others consider the NDP through a flow perspective, evidencing IE and LC (MASCITELLI, 2011; OLIVEIRA, 2017; OPPENHEIM, 2004). Furthermore, a cyclic perspective was found (PARKER, 2017). Four exclusion criteria underpin the NDP by dictating the elimination of solution alternatives.

The elimination of an alternative from the set occurs when it does not meet the desired requirements, is proven unfeasible, is incompatible with the other options from other functions, and is deemed inferior in every attribute (based on facts) (AUTZEN, 2013; FRYE, 2010; MEBANE *et al*., 2011; RAUDBERGET, 2010a; RAUDBERGET, 2010b; RAUDBERGET, 2011). Nevertheless, the moment of application of each criterion is not consensus in the literature. Some approaches suggest that, initially, the exclusion is made based on requirements and feasibility, then by compatibility, followed by a final reduction method (AMMAR *et al*., 2018; FRYE, 2010).

Other approaches propose connecting project requirements and system decisions first, then comparing trade-offs to configurations, and finally, the analysis of trade-offs and limit curves (KENNEDY; SOBEK II; KENNEDY, 2014). Another approach is comparing cost and value of alternatives to verify dominance. Given the same cost, sets providing less value than others are discarded. The same goes for the opposite, i.e., the same level of value with higher costs (WADE, 2018). There is no consensus or in-depth study about the narrowing criterion and their evolution throughout NPD.

The literature demonstrates the evolution of the project in terms of the level of abstraction as the knowledge increases. First, teams consider functions that evolve into physical and working principles. Later, principles are translated into design alternatives, and finally, a final PBD is achieved (SAAD; ROTZER; ZIMMERMANN, 2019). Two SBD principles rule the NDP, which are, 'Establishing feasibility before commitment' and 'Integrating by intersection'. The first comprises the communication that must exist in the NDP, and the second dictates the narrowing of alternatives.

The communication focuses on creating reusable knowledge for a broader audience. It enables a vast and lasting impact on current and future projects (ZHONG; DOCKWEILER, 2020). The ToC support communication in NDP (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2016b; ARACI *et al.*, 2017; ARACI *et al*., 2020; MAULANA *et al*., 2017; MAKSIMOVIC, 2013; MOHSIN; ABDULATEEF; AL-ASHAAB, 2020) along with the *Obeya* room and boards (ZHONG; DOCKWEILER, 2020).

Methods to 'integrate by intersection' were proposed to aggregate sets representing the DS of multiple subsystems (NAHM; ISHIKAWA, 2005; MCKENNEY, 2013; TOCHE, 2017). The means mentioned to overlap DS are virtual prototyping, factory simulation, and interconnectivity with physical prototyping (TOCHE, 2017). Advances were concentrated in DS representation through fuzzy logic to create a combined notation to enable the overlap of feasible areas. Nevertheless, knowledge regarding the intersection process is still incipient. None of the models addressed procedural methods to overlap DS in an NDP context, considering IE and LC.

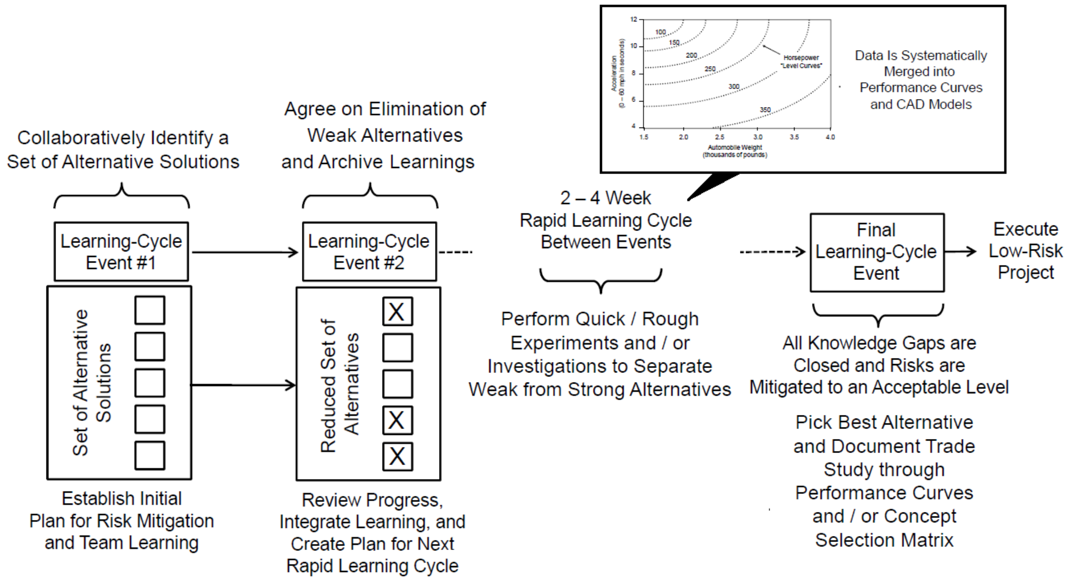
The limited resources for development in the NDP are addressed by controlling the level of testing necessary to make decisions. The intent of SBD is not to test every concept to the highest level of detail but to perform the appropriate amount of testing considering the size of the solution set. During the early stages, when the set is numerous, tests are detailed just enough to expose major problems, demonstrating failures rather than successes. As the set narrows, the depth of tests should increase (BERNSTEIN, 1998).

The literature approaches methods to reduce sets such as the brute force method that relates alternatives for a specific reason without automated tools. Another option is to use design synthesis tools that sample the remaining combinations of solution alternatives. Furthermore, a factor screening can be applied using statistical software with derived prediction coefficients. Finally, a model of complex negotiating functions in statistical software can reduce the remaining combinations to a manageable set for scoring and sensitivity analysis (FRYE, 2010).

Concerning the flow and pace of the NDP, one must mention IE, LC, and the control of the size of the DS. The IE performed in NDP are meetings where work results are comprehensively coordinated, forming a cadence for integration and re-calibration of direction and scope (MASCITELLI, 2011; OPPENHEIM, 2004; ZHONG; DOCKWEILER, 2020). LC and design review and freeze events occur during the NDP, as presented in Figure 2.10 (MASCITELLI, 2011).

LC provide a constant rhythm to the development, comprising a set of quick turn experiments to be concluded on a target date for integrating the new knowledge (MASCITELLI, 2011; OLIVEIRA, 2017; OPPENHEIM, 2004). Methods were proposed to control the convergence of DS (BERNSTEIN, 1998; MCKENNEY; KEMINK; SINGER, 2011; MEBANE *et al.*, 2011), such as prototypes, for example, attributed to each integration event (BERNSTEIN, 1998). The convergence process will happen in different rhythms in each subsystem due to the particularities of the problem, LI intended, and complexity, among other factors (FRYE, 2010).

Figure 2.10. Learning cycles in set-based design



Source: Adapted from Mascitelli (2011)

Subsystems can be designed in a different strategy, apart from the NDP, based on the following criterion: (1) they converge to a point (FRYE, 2010); (2) they have an insignificant parameter range compared to the system performance. For the latter, the best design choice is to fit the system set, i.e., to adopt the PBD strategy (AUTZEN, 2013; KHAN *et al.*, 2011). An innovative model is the reactive multi-agent system, which consists in generating space and locating agents representing solutions, constraints, contradictions, and specifications. Each agent will repulse or attract the alternatives. A feasible area inside this space is defined and solutions can be discarded depending on their final position (DAFFLON *et al.*, 2016).

The narrowing-down of alternatives is performed by the exploration of subsystems sets in parallel (through simulation, analysis, experiments, ToC, and prototypes), and the elimination of incompatible and unfeasible solutions based on intersections between DS, as presented in Table 2.5. Manufacturing participation during the NDP is a source of information that bounds and narrows the DS (ESSAMLALI; SEKHARI; BOURAS, 2017; KAO, 2006; KHAN *et al.*, 2011; KERGA; KHAN; ARIAS, 2012a; KERGA; TAISCH; TERZI, 2012b; MASCITELLI, 2011).

Table 2.5. Most cited activities and tools for the narrowing-down process

Activities and tools	Authors
Define solution sets for design trade-offs exploration	Ammar *et al.* (2019a), Araci *et al.* (2017), Araci *et al*. (2020), Autzen (2013), Bernstein (1998), Essamlali, Sekhari, and Bouras (2017), Khan *et al.* (2011), Maulana *et al*. (2017), Parker (2017), Shallcross *et al*. (2019), Toshon *et al*. (2017), Ward *et al.* (1995)
Establish the preference of designers	Frye (2010), Mckenney, Kemink, and Singer (2011), Mebane *et al.* (2011), Khan *et al.* (2011)
Explore sets concurrently through simulation, analysis, experiments, ToC, prototypes and tests	Ammar *et al*. (2019b), Ammar *et al*. (2019c), Araci, Al-Ashaab, and Maksimovic. (2016a), Araci *et al.* (2016b), Araci *et al.* (2017), Araci *et al*. (2020), Araci, Al-Ashaab, and Almeida (2021), Autzen (2013), Blindheim *et al.* (2020), Essamlali *et al.* (2017), Khan *et al.* (2011), Maulana *et al*. (2017), Parnell *et al*. (2019), Raudberget (2011), Shallcross *et al*. (2019), Small (2018); Specking *et al*. (2018a), Ward *et al*. (1995)
Communicate sets and understand constraints	Ammar *et al.* (2019a), Autzen (2013), Khan *et al.* (2011), Parker (2017)
Define filtering criteria	Al-Ashaab *et al*. (2013), Araci *et al.* (2017), Essamlali, Sekhari, and Bouras (2017)
Determine set intersections by feasible sets integration	Ammar *et al.* (2019a), Ammar *et al*. (2019b), Ammar *et al*. (2019c), Bernstein (1998), Khan *et al.* (2011), Maulana *et al*. (2017), Parker (2017), Parnell *et al*. (2019), Raudberget (2011), Small (2018), Specking *et al*. (2018a)
Gradually narrow-down the sets through cycles of development, analysis, and test	Ammar *et al.* (2019a), Araci *et al.* (2017), Autzen (2013), Bernstein (1998), Essamlali, Sekhari, and Bouras (2017); Frye (2010), Mascitelli (2011), Maulana *et al*. (2017), Mckenney, Kemink, and Singer (2011), Mebane *et al.* (2011), Parker (2017), Parnell *et al.* (2019), Raudberget (2010a), Raudberget (2010b), Raudberget (2011), Small (2018), Specking *et al*. (2018a), Ward *et al.* (1995).
Evaluate sets for lean manufacturing, maintainability, sustainability, assembly, reliability, and safety	Autzen (2013), Al-Ashaab *et al*. (2013), Borchani *et al*. (2019), Essamlali, Sekhari, and Bouras (2017), Khan *et al.* (2011), Ishikawa and Sasaki (2020)
Seek conceptual robustness against variations	Autzen (2013), Bernstein (1998), Khan *et al.* (2011), Toshon *et al.* (2017)
Control the narrowing process establishing gates	Bernstein (1998), Mascitelli (2011), Shallcross *et al*. (2019)
Plan for manufacturing and select suppliers	Autzen (2013), Khan *et al.* (2011)
Converge on the final set of subsystem or product layout	Ammar *et al*. (2019b), Ammar *et al*. (2019c), Autzen (2013), Essamlali, Sekhari, and Bouras (2017), Khan *et al.* (2011), Maulana *et al*. (2017), Parnell *et al*. (2019), Small (2018), Specking *et al.* (2018a), Toche (2017), Toshon *et al*. (2017)
Analyze final set regarding risks	Autzen (2013), Parnell *et al*. (2019), Small (2018), Specking *et al.* (2018a)

IE and specific events as the design, process, and production (3P) enable considering fabrication issues, such as 'critical-to-quality' and 'critical-to-cost' (MASCITELLI, 2011). Manufacturing events focus on presenting tools to improve cost, quality, and manufacturability. Furthermore, optimisation activities are performed, such as the Design for X (DF-X) along with line design, equipment readiness, fixturing, *poka-yoke*, flow, takt time, and capacity constraints analysis (MASCITELLI, 2011).

The DS exploration is made according to a design and manufacturing perspective. It forms a base for ‘imposing minimum constraint’, one of the elements of SBD. Attributing flexibility to manufacturing and delaying specifications is the path to a robust design (KERGA; KHAN; ARIAS, 2012a; KERGA; TAISCH; TERZI, 2012b; TOSHON *et al*., 2017). The main idea behind the participation of manufacturing in the NDP is that for each alternative solution, there are alternative process chains to investigate from a manufacturability perspective (KERGA; KHAN; ARIAS, 2012a; KERGA; TAISCH; TERZI, 2012b).

A four-step method was proposed to perform the process planning and evaluation of each alternative to support manufacturing. First, the key quality characteristics for alternative sets of designs are defined. Then, the process quality is planned through QFD and Failure Mode and Effect Analysis (FMEA). After, process quality and cost for each set of designs are assessed. Finally, it is necessary to build a decision matrix relating conceptual design alternatives concerning process-chain alternatives (KERGA; KHAN; ARIAS, 2012a; KERGA; TAISCH; TERZI, 2012b).

Some authors claim that the DF-X is applied during the NDP (KAO, 2006; LERMEN *et al*., 2018; MASCITELLI, 2011). After the narrowing based on quality issues, when just feasible and acceptable solution alternatives remain, the NDP is finished by evaluating cost, logistics, and manufacturability, among other desirable attributes. The main tools in the DF-X stage are Computer-Aided Design (CAD) and the planning/design of manufacturing process matrices of QFD (ESSAMLALI; SEKHARI; BOURAS, 2017; KAO, 2006).

A mathematical framework was proposed to optimise contribution-to-design functions from different alternatives in each iteration to support decision-making (RAPP *et al*., 2018). Furthermore, the engineering reasoning in SBD was modelled, claiming that SBD and PBD have the same deductive reasoning during development. Given the variables and the knowledge, engineers derive specifications. Nevertheless, the difference between the two strategies lies on the timeline in which decisions are made and the method is used to generate solutions (WHITCOMB; HERNANDEZ, 2019).

2.4.4 Outputs of the narrowing-down process

The NDP ends when a sufficiently small region in the DS remains, in which all the options are feasible, compatible, and differ very little in performance. Despite the usual speech of 'one single solution remains', it is not (or almost not) possible. Especially considering that if one respects the premises of robust design, the manufacturing tolerances will stay open until the end of the process, corresponding to more than one solution. In this scenario, the development team chooses the winning alternative. This choice follows the interests of the developers, which can be the lowest possible cost, the best design, or the best manufacturability, among other aspects.

The development after the NDP follows PBD cycles or traditional development approaches (MEBANE *et al*., 2011; KENNEDY; SOBEK II; KENNEDY, 2014). These approaches are usually strongly supported by decision matrixes, as the method of Pugh, to choose the best option among a universe of previously narrowed-down solutions (FRYE, 2010; MAULANA *et al*., 2017). Once the final solution is chosen, the detailed design begins (KHAN *et al*., 2011; LERMEN *et al*., 2018). It is performed by releasing the final specification of the product, including its tolerances and values of parameters (provided by manufacturing), 3P (Production, Preparation, Process), value engineering, and the entire system definition (KHAN *et al*., 2011; LERMEN *et al*., 2018).

Defining the LI intended and planning the development strategy of each part affects the end of the NDP. Depending on the resources available, only parts of the system will be developed in an SBD strategy. The components that do not require a high LI and are well-known by the organisation can follow traditional methods of development in a hybrid approach (SCHULZE, 2016). In this case, the non-SBD alternatives are chosen to fit the narrowed-down solutions after the NDP.

2.5. ANALYSIS OF MODELS AND FRAMEWORKS FOR SBD

The results of the SBR carried out in this research demonstrated the absence of a comprehensive model for SBD, presenting inputs, outputs, and detailing the NDP. The models and frameworks generally comprise tools to assist in finding, selecting, and representing the DS and provide general guidelines for parts of the SBD. Even though many efforts were made to present early-stage methods and quantitative, computational, and engineering design-oriented models, little was advanced toward a complete process of SBD, enabling its implementation.

The management of the NDP is the most relevant absence in the literature. Since the knowledge in this field of study is dispersed in several publications focusing on specific parts of the strategy, consistent guidelines for a well-established SBD are missing. The initial modelling of SBD, as reported in the literature, was made with managerial models, as presented in Figure 2.11. Models addressing a specific activity and 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 toward 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 emphasising 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. The inputs for the NDP are widely approached, presenting tools, steps, and techniques for value research, definition and deployment, development planning, DS mapping and representation, and CS or initial DS bounding. Value definition is the activity most mentioned in the literature regarding the early stages of development.

Ten gaps and opportunities emerged from the SBR analysis (Fig. 2.11). Even though many works discuss value in LPD, little is approached concerning value deployment. Only the model of Oliveira (2017) and Pessoa and Trabasso (2017) demonstrated value deployment in an LPD environment. The work of Oliveira (2017) defined and deployed value for subsystems with QFD focusing on the second deployment level, demonstrating subsystems and components characteristics matrices. Nevertheless, QFD has more deployment levels, including production planning and planning for process control.

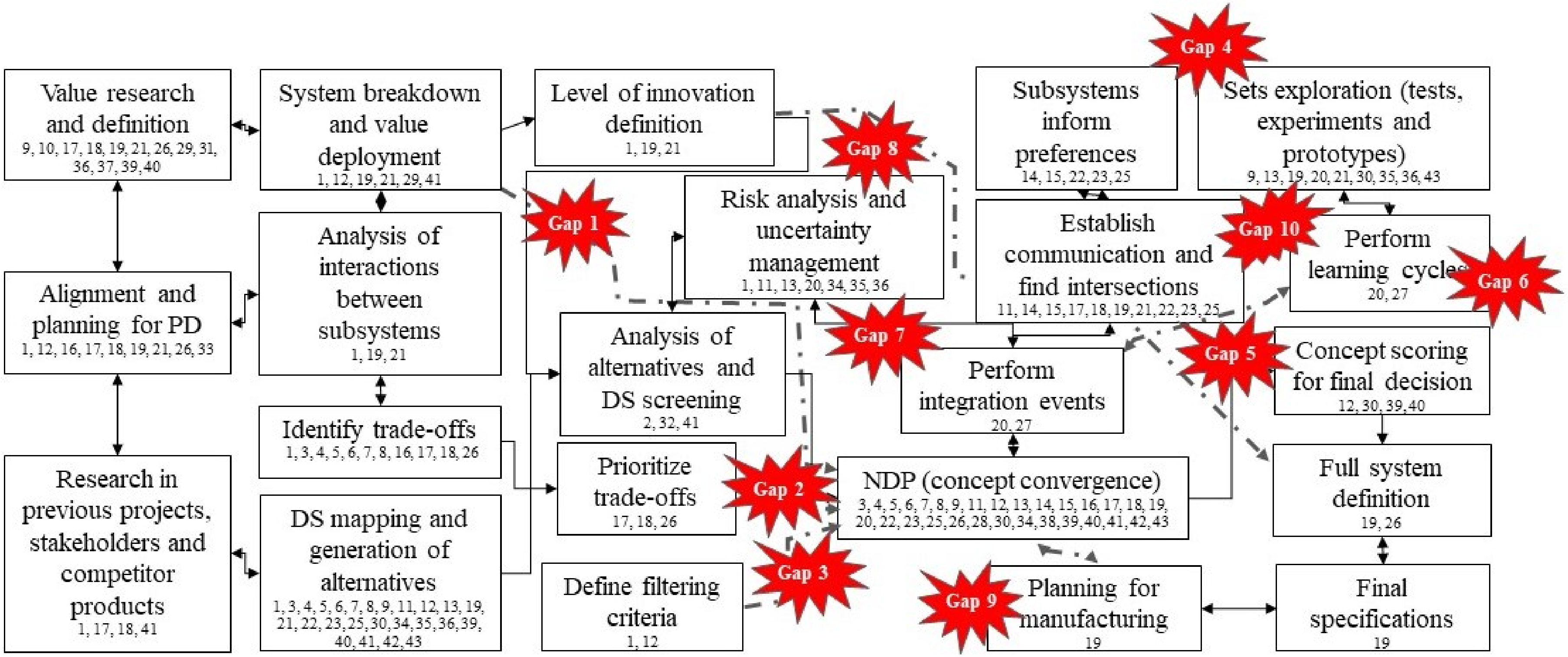
QFD is a consolidated tool in PDP. Nevertheless, the problem lies in its application in LPD and the use of its information to narrow down the DS with IE and LC (Gap 1, Fig. 2.11). Connecting value deployment and the NDP is necessary to enable SBD implementation. The literature widely mentions but does not demonstrate and detail the role of systems contradictions or trade-offs. Nevertheless, methods for the identification of design trade-offs (KERGA *et al*., 2014; OLIVEIRA, 2017; OLIVEIRA *et al*., 2018), ToC generation and analysis (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI *et al*., 2020; ARACI; AL-ASHAAB; ALMEIDA, 2021) can be found.

The models complement each other as they form the knowledge basis to generate the ToC and to find and prioritise the contradictions involved in the project. Nevertheless, their application in IE and LC and their connection with the NDP remains a gap in the literature (Gap 2, Fig. 2.11). Planning activities for conducting SBD are not widely cited among authors, even though they are crucial since several subsystems develop the product in parallel. It demands at least a minimum level of activity coordination through planning information flow, decision-making, and IE. Oliveira (2017) and Mascitelli (2011) proposed a tool called DR. Furthermore, the Toyota Kata (TK) approach was brought as a solution for LC management (OLIVEIRA *et al*., 2018).

A crucial factor to be considered when modelling SBD is the limitation of resources in product development. Workforce, costs, technology, and strategic issues associated with the organisation constrain the product and the development process. Thus, it is crucial to properly use the available capacity, avoiding waste and concentrating efforts on the regions of the DS that present more chances of success. Many works approached this issue by proposing an initial CS to reduce DS and balance resources with design efforts. Another approach is the definition of the LI. Narrowing down solutions demand a heavy amount of resources, and reducing the size of sets implies cost reduction.

Numerous contributions approached CS, but little literature underpins the LI in SBD. Schuh, Rudolf, and Luedtke (2016) addressed the decision regarding the development strategy for each concept against initial filtering criteria. Based on the LI, subsystems and components are designed following different paths. Nevertheless, guidelines are missing to support the decision-making on the LI. Works mention the possibility of a hybrid development strategy, but they do not demonstrate the procedure behind designing a product with SBD and PBD simultaneously (Gap 8, Fig. 2.11). Naturally, integration issues are the core of a hybrid strategy since the DS narrowing poses restrictions in the PBD domain. Thus, research regarding planning and managing resource constraints to enable SBD is the most relevant field of study identified in this SBR.

Figure 2.11. 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).

Source: Adapted from Oliveira *et al*. (2022a)

Previous knowledge bounds the DS and generates alternatives front-loading the NDP. Nevertheless, models and frameworks do not provide procedures for storing and reusing knowledge, except for ToC. It constitutes a relevant gap in the literature on SBD due to the importance of knowledge management in the PDP. Some works approaching initial filtering techniques presented traditional tools as decision matrices to measure the potential convergence of the solution. According to a theoretical/conceptual perspective, CS is an activity that opposes the principles of SBD since it is supported by the evaluation and attribution of scores for alternatives. SBD preconises decision-making based on proven facts and not on guesswork. The problem with concept scoring is that generally, no solid knowledge background exists to prove an alternative better or worse in the early stages.

Another initiative to balance DS with the resources available is to control the amount and depth of the experiments performed at each LC to avoid unnecessary work. Testing every concept to the highest level of detail possible can be considered waste. There is an appropriate level of detail dictated by the size of the set of subsystems at each stage of development, as affirmed by Bernstein (1998). It represents an important step toward balancing activities. Nevertheless, it was just mentioned in the literature with no model or procedure to address and demonstrate this issue.

The DS mapping and representation is vastly approached in literature, focusing on emphasising the preference of designers. Depending on development goals, certain regions of the DS are more suitable than others. DS mapping is a consolidated field in the literature with several notations proposed, most assisted by fuzzy logic. Rosen (2015) made a relevant advance in DS representation by introducing the possibility of different abstraction levels. It has the potential to bring better DS visualisation, especially regarding requirements associated with structural, mechanical, and physical performances. Furthermore, connecting this multilevel representation with IE and LC may be the path for SBD integration with manufacturing.

The literature does not explore the involvement of suppliers and manufacturing in the early stages and during the NDP. It is one of the greyest areas in SBD, evidenced by the lack of research demonstrating the third and fourth levels of QFD. The principles of SBD dictate the participation of stakeholders in the NDP toward a robust and viable design. Mascitelli (2011) mentioned special IE to input information from manufacturing for decision-making in the NDP. Still, many questions arise regarding this subject, which is crucial for SBD implementation. The contribution of manufacturing in the NDP, experimentation, and assistance in closing design tolerances, management of constraints arising from production, and the planning of tools, processes, and production flow are not evident (Gap 9, Fig. 2.11).

The literature presents two perspectives regarding the NDP. One is to consider the DS as a space of solutions with infinite possible values for each parameter. Other is to work with discrete solution alternatives representing points in the DS. The implication is the necessity to generate concepts of solutions to test during the NDP instead of focusing on operation regions. Lee (1996) addressed the problem by affirming that a DS is complex to evaluate and narrow down. Thus, alternative solutions are necessary to represent regions and enable experimenting. Hence, the literature soaks to model techniques to find the best alternative solutions in a feasible DS. Nevertheless, setting and testing solution concepts are complex in projects subject to severe resource restrictions and knowledge limitations. According to the particularities of each case, considering regions instead of solutions alternatives may be more appropriate. It is a possible field of study to advance knowledge in SBD.

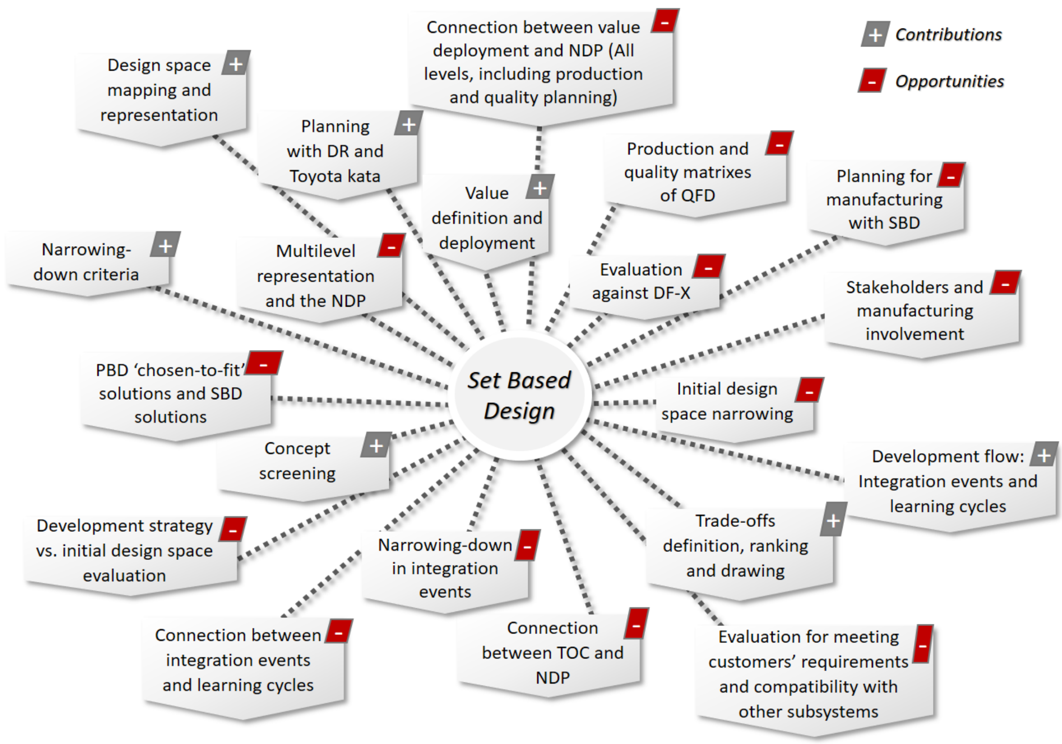
The literature agrees upon the general criteria to narrow down solutions. They are meeting CR, the feasibility of solutions, compatibility with other subsystems, and, finally, being proven inferior. Few procedural methods for set evaluation following these criteria are approached (Gap 3, Fig. 2.11). Publications affirm tests, comparisons, and the QFD matrices as the path to identify inadequateness concerning requirements meeting and solution feasibility, enabling to discard alternatives. Nahm and Ishikawa (2005) and Mckenney (2013) were pioneers in presenting methods to verify compatibility between subsystems. Nevertheless, there is room for further advance in comparing DS and deciding based on the compatibility criteria (Gap 10, Fig. 2.11).

Experimentation results principally in ToC, limit curves, and relations between variables. Nevertheless, regarding their management and planning, few are mentioned in publications (Gap 4, Fig. 2.11). Oppenheim (2007) pioneered detailing the LPD flow evidencing IE and LC to answer crucial design questions. Nevertheless, the procedure concerning the conduction, integration, planning, and synchronisation of LC and IE is missing in the literature (Gaps 5, 6, and 7, Fig. 2,11). Subsystems converge in different rhythms. Hence, managing and orchestrating the NDP with several subsystems is a challenge. Oliveira (2017) proposed the DR to plan and visualise the cadence of experiments and decision-making, synchronising related decisions from different subsystems and respecting precedence relations.

After the NDP, two possible outcomes are mentioned in the literature. One is a final solution representing a point in the DS other is a sufficiently small solution set for each subsystem representing a region in the DS. In this case, sets are evaluated against the preferences of designers to find a winning solution. Decision matrices are tools to assist in set evaluation against desired criteria. Another technique to choose and develop the final solution to the point of launching and production is the DF-X. Nevertheless, the integration of this technique with the SBD is missing in the literature.

Works that propose models and frameworks for the SBD presented advances concentrated mainly in the early stages of development and little in the NDP. Many authors cite several tools, techniques, principles, and elements associated with the NDP, but little is demonstrated or modelled regarding the subject addressed. The outcomes of the SBR prove the relevance of the research problem approach in the Doctoral Dissertation. The absence of comprehensive managerial models to assist the implementation of SBD is a hindering factor to its adoption. Therefore, based on the previous analysis, the main contributions and gaps found in the literature are presented in Figure 2.12.

Figure 2.12. Main contributions and gaps found in the literature



Source: Oliveira *et al.* (2022a)

2.5.1 Requirements for a managerial model and process for set-based design

The state-of-the-art presented in the previous sections discussed the outcomes of the SBR analysis by presenting the main gaps and opportunities for further advancing knowledge about SBD. It paves the way for new detailed, robust, and implementation-oriented models, providing the tools for spreading SBD and its benefits. Because of the dispersion of knowledge in this field of study, the gaps identified are mainly related to linking information, steps, and activities in SBD. Even though some subjects are widely discussed, models rarely address more than one part of the SBD. It poses the necessity to advance toward holistic and comprehensive managerial models to connect and detail the development process in SBD environments.

Most efforts are concentrated in the early stages; nevertheless, they are not translated into a vast knowledge background regarding front-loading the NDP with solution alternatives and information. The NDP is the most value-added part of SBD, and even so, the literature lacks detail. Connecting inputs for the NDP and the process itself, which includes value definition and deployment, planning of LC and IE, CS activities, LI definition, ToC, and DS mapping is one of the most crucial advances in this field of study.

The flow of the NDP is also a grey area in the literature, i.e., IE, LC, experiments, ToC application, narrowing-down criteria, 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 DS size are fundamental since it is mentioned among publications as hindering factor to SBD adoption. Strategies for balancing the DS and resources must also be further explored.

Techniques to provide compatibility between resources available and demanded are necessary. Not only methods such as CS and the definition of the innovation level but controlling the amount and depth of experiments and the maturity of concepts. The gaps and contributions presented in this SBR provided a background for eliciting requirements to guide the development of managerial models that can foster SBD implementation:

1 Demonstrate the contribution of value deployment for the NDP;

2 Demonstrate the generation and contribution of ToC during the NDP in the context of IE and LC;

3 Demonstrate how LC and IE are connected and present a method integrating them;

4 Present a method for LC and IE management and execution;

5 Methods to decide on the LI of each part;

6 Present a hybrid development strategy model integrating SBD and PBD;

7 Approach the participation of stakeholders and manufacturing in the NDP evidencing their contribution to DS reduction;

8 Presenting techniques to support decision-making regarding balancing DS;

9 Model the knowledge capture, management, and storage in SBD;

10 Present a comprehensive model for the product development flow in SBD.

2.6. CONCLUSION

This Chapter presented the theoretical background of SBD with the concepts, principles, practical implications, and advances found in the literature. Studies on SBD showed that among the strategies of solution convergence for product development, SBD presents the best results, lower risks, and promotes an enabling environment for innovation. Many authors claim that factors associated with integration, learning focus, and organisational culture are intrinsically correlated with the success of SBD implementation. It was concluded that these factors must be taken into consideration for developing a model and process for SBD.

The outcomes of the SBR were presented in this Chapter, providing the support to achieve the Doctoral Dissertation objectives. The review question was to discover the models and frameworks for the SBD in the literature. It was found 121 works reported in 35 scientific journals, 31 proceedings of international conferences, 1 book, 11 Master Theses, and 11 Doctoral Dissertations. It was concluded that most publications approach ToC, multiscale design, DS 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’. The main findings of the SBR are summarised:

1 It was not found any work that addresses SBD broadly since none approaches inputs, outputs, and the NDP simultaneously;

2 There is a notable focus on explaining the SBD methods and techniques for early stages in the development process and little enlightenment in NDP;

3 It was observed that authors consistently agree on the lack of models that can support SBD adoption. This gap is currently not filled;

4 ToC, manufacturing, and supply chain involvement, LC, IE, narrowing-down criteria application are widely mentioned as practical SBD enablers but they remain scarce in the literature;

5 Although prototyping, testing and experimentation are addressed as keys to SBD to foster decision making, these practices are rarely found in literature and no model presented their use in the NDP.

SBD demands more resources than the PBD, which is a hindering factor in adopting this strategy. Advancing knowledge toward solutions to this problem is essential for SBD dissemination. Knowledge management is approached mainly by techniques for DS mapping in several publications, including ToC. Introducing the possibility of different abstraction levels in DS representation and the storage and usage of knowledge in SBD environments are opportunities. Regarding quantitative, computational, and/or engineering-oriented models, it was concluded that the focus of the literature is CS and techniques for filtering and communicating the DS during the NDP. The most applied technique is fuzzy arithmetic.

Many gaps that may hamper SBD implementation efforts were identified through this research. It was observed that most of them represent connections between information, steps, and activities in SBD. It is a consequence of the dispersion of knowledge in the field and the absence of holistic and comprehensive models. Advancing toward models that connect and detail the development process in SBD environments is necessary. It implies difficulty for development teams to adopt this strategy, even though its superiority over traditional product development approaches is known and recognised.

CHAPTER 3

A MANAGERIAL MODEL AND PROCESS FOR SET-BASED DESIGN

This research aims to build a referential comprehensive managerial model and process for SBD, closing the knowledge gaps to foster and expand LPD adoption and successful cases. It represents the pioneer effort to gather and model the entire SBD flow, including value deployment, ToC generation, resource balancing, and development strategy definition for each part of the product, IE, LC, planning for LPD, and knowledge management. This Chapter presents the core of the research, concretising the development and detail of SBD, underpinned by the findings presented in the previous Chapter.

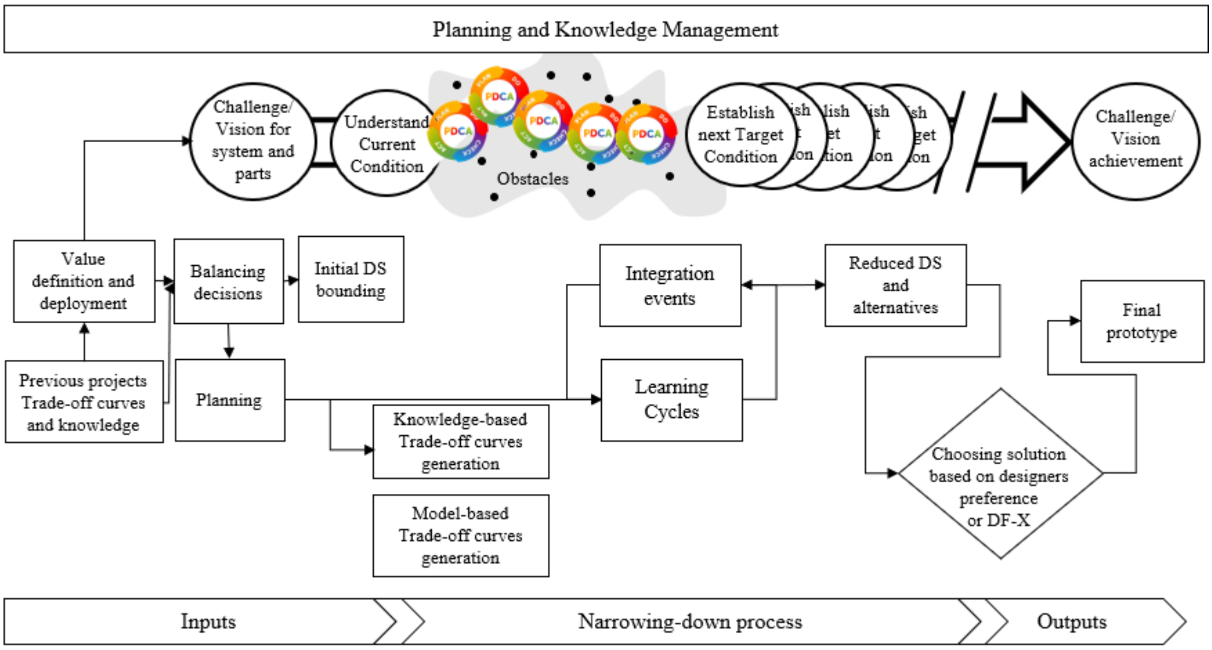
Seven sections compose this Chapter, following the logic proposed for conducting SBD. Section 1 introduces and outlines the model and process, aiming to prepare and guide the reader to understand the subsequent sections, which approach specific parts of the proposal. Section 2 deals with the centre of any lean initiative, i.e., value definition and deployment for LPD. Section 3 presents the process of model-based and knowledge-based ToC generation to support the evaluation of alternatives and DS areas during the NDP.

Section 4 comprises one of the most crucial factors affecting the SBD adoption, i.e., balancing DS and resources available for design. Section 5 connects value, trade-offs, and balancing strategies under the NDP umbrella, presenting the development flow in SBD. Section 6 discusses planning for SBD and RBM. Finally, Section 7 concludes the chapter by comparing the knowledge gaps and contributions of the literature and the model and process for SBD proposed in this research.

3.1. OVERVIEW OF THE MANAGERIAL MODEL AND PROCESS FOR SET-BASED DESIGN

As previously mentioned, SBD can be considered a transformation process by which inputs (value, information, planning, knowledge, and initial DS) are transformed into outputs (single solution for each part of the product) through the NDP. The inputs are all the activities, research, and decisions that gather sufficient knowledge and prepare the tools and designers for studying and eliminating DS regions and alternatives. Figure 3.1 presents the overview of the model and process for SBD.

Figure 3.1. Overview of the model and process for SBD



The outcomes of the NDP are knowledge from extensive experimentation and the final solution (product and/or service) provided to customers and stakeholders. The journey of designers to develop the product consists of short PDCA cycles that enable them to produce knowledge to support decision-making. These cycles are organised in a synchronous cadence of LC and IE, aligning all subsystems and manufacturing toward the challenge (value). The managerial model and process proposed in this research aim to gather all parts of the transformation process, connecting activities and elements to provide a comprehensive guide to SBD.

SBD starts when designers perform the value definition and deployment, which rules the entire NDP process. The research demonstrates how the Quality Function Deployment (QFD) framework is the flag that all designers and teams will pursue. It is also the path to integrate lean manufacturing and LPD since the early stages of the product life cycle. Based on value definition and deployment, designers perform three main activities. The first is to prioritise and plan ToC generation, front-loading the NDP with alternatives and the tools to analyse them. The second is to study and seek strategies to balance resources and the DS size. The bigger the DS area, the more expensive its exploration is regarding the number of experiments, money, time, and people.

Product development poses a scenario where limited budgets, deadlines, and teams exist. Conducting SBD to its full extent, considering the entire product under its umbrella may be prohibitive. Fostering SBD adoption means creating a managerial method that embraces these restrictions by offering feasible solutions. The third activity following value deployment is the initial DS bounding, which is a direct result of establishing initial range values for each design parameter based on customers' requirements at the system level. Before and during the NDP, planning, and knowledge management prepare and guide the cadence of the development activities, establishing milestones and target knowledge conditions to be pursued by designers.

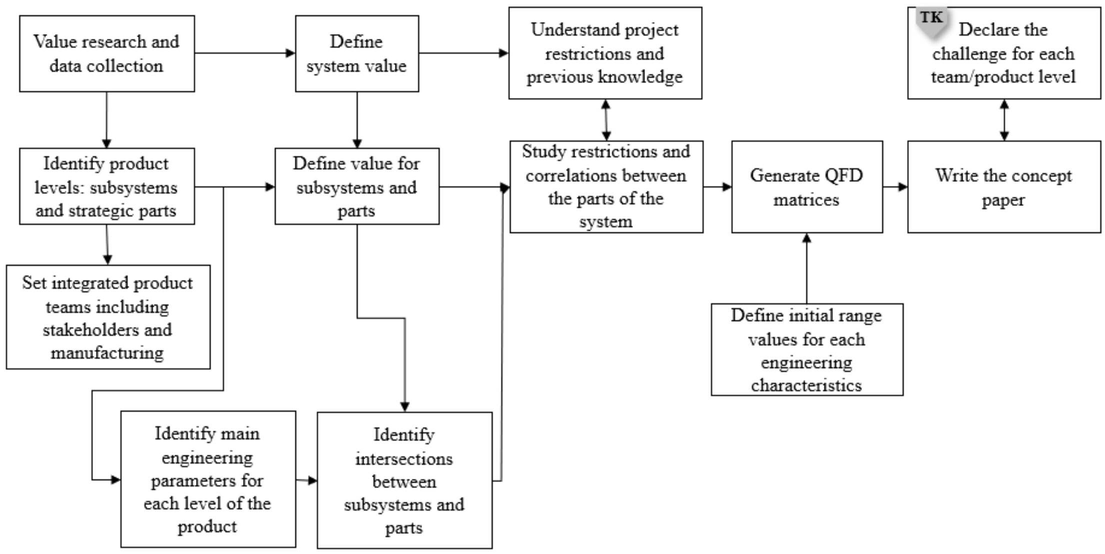
All these activities and their outcomes provide an environment where alternatives and DS areas can be narrowed based on the four criteria of SBD: unfeasibility, incompatibility, absolute inferiority, and incapability to deliver the required value. The NDP is then orchestrated in IE and LC until the DS is sufficiently small or only a single solution remains for each subsystem and part, enabling the final assembly or prototype of the product. The inclusion of DF-X issues can be considered to evaluate the final solutions to choose a winner based on the preferences of designers.

3.2. VALUE DEFINITION AND DEPLOYMENT

Any lean initiative starts by understanding value. It would not be different in LPD. The role of value in PDP is to guide every decision-making, every activity or experiment, and to align all development teams toward a common goal. The better the value is defined and translated, the more chances of success. Besides customers, other sources assist in understanding value, such as analysing competitors, identifying state-of-the-art technologies and literature, studying physical and mechanical phenomena associated with the product, and researching previous projects and knowledge.

Figure 3.2 expands the contributions made in the Master's research preceding this Doctoral Dissertation (OLIVEIRA, 2017) to present the proposed model for defining value. The main outcome of this activity is a document known as 'Concept Paper', which represents the consolidation of an in-depth study of the market and the characteristics and objectives for each product level. This report contains guidelines for all parts of the product, detailing their contribution to achieving the required performance and delivering value. Furthermore, it declares the challenge for each development team (see section 3.5.1).

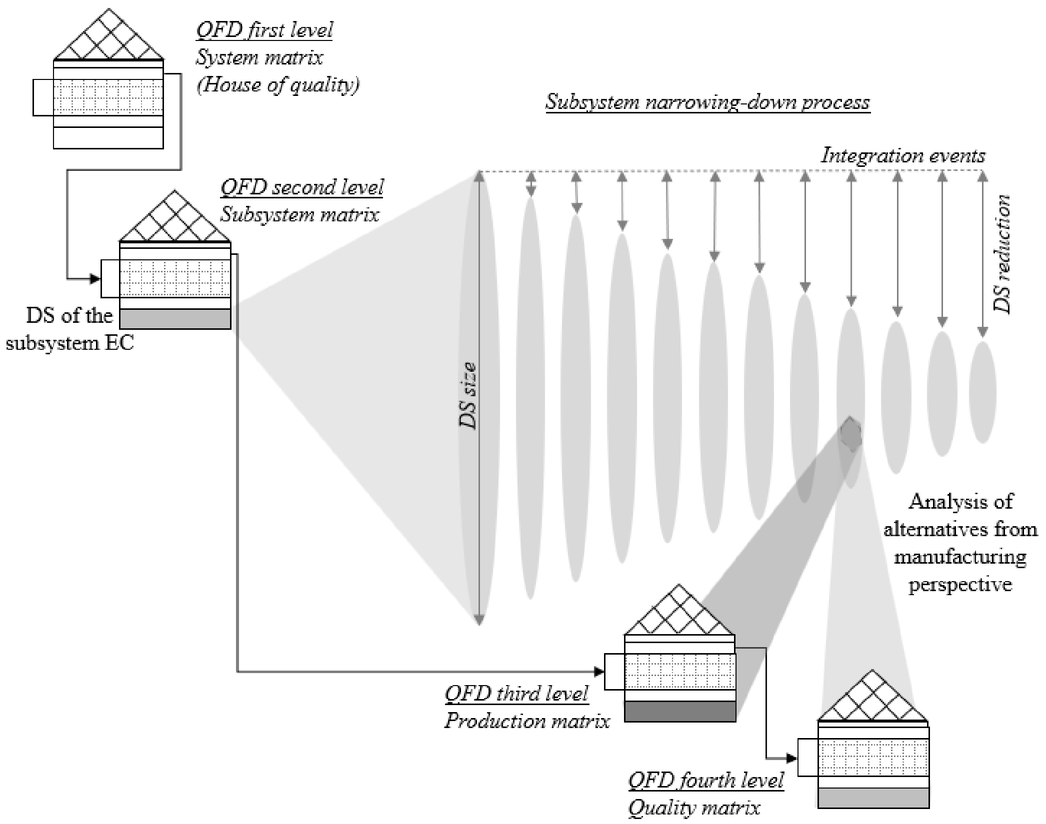
Figure 3.2. Model for value definition and deployment



The activities preceding the concept paper aim to provide enough information to declare and write a complete overview of the project and to translate value into Engineering Characteristics (EC), enabling the alignment of efforts and plans for achieving objectives and goals. The QFD underpins the entire value definition and deployment for each product level. Most of the information gathered during this stage is represented in its matrices, guaranteeing the alignment of subsystems toward value. The lack of clarity about the role and performance of each part compromises their integration to compose the system. Thus, the QFD framework promotes clarity, integration, and alignment of subsystems toward value. Figure 3.3 presents the QFD framework and the SBD flow.

PBD works by designing products pursuing target values for each EC, i.e., points in the DS. For this strategy, the relative importance of EC based on the CR ranking is crucial as it significantly impacts the target value setting of characteristics (DU; LIU, 2021). Thus, the focus lies on the first level of QFD since it results in a target value for each EC. In opposition, SBD environments adopt QFD not to provide targets but to delimit value ranges. The strategy is named SBD since it considers range values corresponding to sets of admissible values for each EC in all its levels, from the house of quality to the quality matrices.

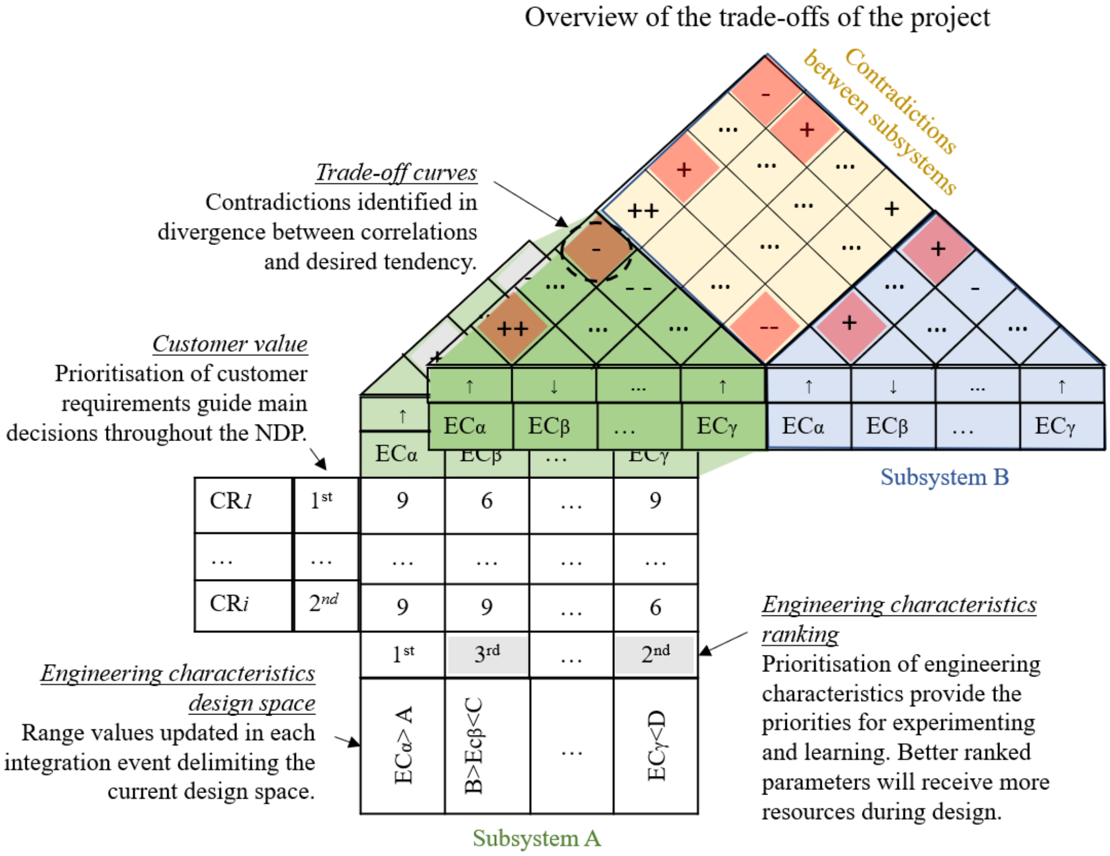
Figure 3.3. Set-Based Design and the Quality Function Deployment matrices



Source: Oliveira *et al*. (2023b).

PBD considers the QFD a static matrix establishing target values to pursue throughout the development. SBD has a different perspective, placing the QFD as a set of living documents and updating the ranges of values at each integration event. The subsystems compare their DSs with the knowledge acquired so far and discard inferior or unfeasible regions that do not provide the necessary performance. In this way, the QFD references the entire NDP. Each part of the matrix has a specific role in the development process, providing outputs for the conduction of the SBD (Fig. 3.4). The first is the relative importance of each EC, guiding the decision regarding the amount of effort required to develop each part of the product, i.e., the size of the DS that is necessary to consider.

Figure 3.4. Quality Function Deployment matrices and the SBD.



Source: Adapted from Oliveira *et al*. (2023b) and Oliveira (2017).

The second is the initial range of values delineating the DS and inputs the NDP. The third is the overview of trade-offs, which will enable trade-off studies and planning for ToC generation. The fourth is the assurance of consistent value deployment from the customer to all product levels (OLIVEIRA *et al*., 2023b). The roof of matrices presents the trade-offs of the project when the desired behaviour of parameters is different from their actual correlation (OLIVEIRA, 2017; OLIVEIRA *et al*., 2023b). Not only ToC but curves coming from failure tests and parameters that do not constitute contradictions are input for the NDP. The decision regarding which parameters to study and focus on comes from the EC ranking. Deploying value assisted by QFD means connecting and enhancing the compatibility between the DS of parameters at all levels, from system to production.

The first level of QFD, also known as the house of quality, grasps the customer value and links it to the product to establish guidelines for the entire development process. This matrix provides range values for system EC. The second level of QFD connects the system EC with the subsystem EC, establishing the contribution of each part to the overall performance. Further deployment can be made to address components and parts with considerable influence on the performance. The value deployment of the system to the subsystems underpins the NDP since subsystems consider the second-level matrices as a reference for achieving the desired result.

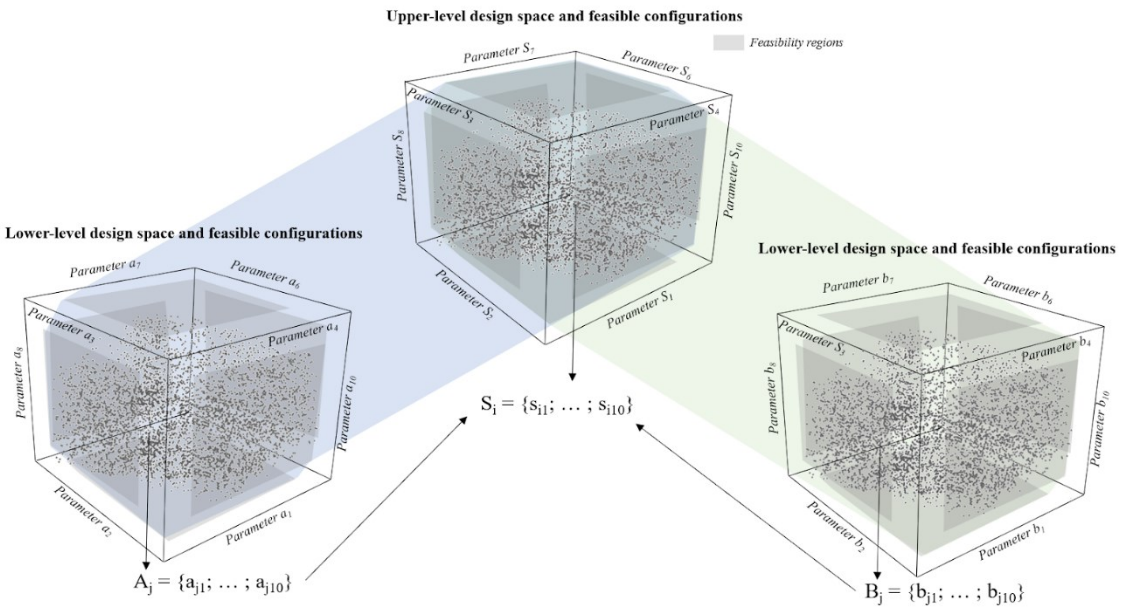
The execution of the NDP leads to delineated DS and enables considering limitations and production issues. Manufacturing-related QFD levels (quality and process matrices) offer the perspective of the fabrication and process capability for producing the considered alternatives. They dictate the establishment of tolerances and accepted variations to compose the final project later in the development since SBD advocates late decision-making to gather as much information as possible.

Teams developing subsystems are composed of several specialties that cover all aspects of the product. SBD preconises the inclusion of manufacturing staff to ensure manufacturability, keep costs under control, and consider logistics issues. The manufacturing staff assists the CE in monitoring compatibility between DS and the third and fourth level QFD matrices. These matrices have increasing importance as the DS diminishes and the NDP advances (OLIVEIRA *et al*., 2023b). The entire QFD framework is necessary to enable SBD and not only the house of quality, as in the case of PBD.

Rosen (2015) affirmed that the DS is propagated through levels, up and down, back and forth (see Fig 2.8). The connection between DSs in different levels of the QFD confers consistency for the value deployment. In other words, taking the first and second QFD level as an example, every possible and viable combination of alternatives for subsystems lead to a point in the DS of the system. Thus, the DS is propagated on a multi-level scale through all QFD levels, as presented in Figure 3.5.

The upward and downward propagation of the DS is the path to integrate the manufacturing perspective in the NDP (OLIVEIRA *et al*., 2023b). The production levels analyse the current DS of components and parts and understand the fabrication processes and parameters that provide the required quality and performance. Production planning, simulations, rapid prototyping, and mock-ups can be vastly employed to verify the viability and manufacturability of alternatives. Considering Design for Manufacturing (DFM) principles when narrowing the DS means establishing the connection between solutions and fabrication.

Figure 3.5. Upward and downward propagation of the design space.



Source: Oliveira *et al*. (2023b).

The matrices of the third and fourth levels provide information regarding the most critical processes for the component and base decisions on final specifications. The link between manufacturing and design is fundamental to defining the tolerable variances to deliver value and machine and tool configurations. Lean manufacturing starts with a project that considers the need to improve manufacturing processes and changes in the site, dedicated lines implementation, analysis of setup times and complexity, and impacts on the overall cost.

CR Event marks the finalisation of value definition. It is a workshop that aims to formally present value definition and deployment results, gathering leaders, teams, stakeholders, and manufacturing to consolidate their alignment and understanding regarding value (MASCITELLI, 2011). It is crucial to highlight that the LPD considers all documents produced as living documents that must be improved and updated as development advances and knowledge is gained. They guide each development activity and decision-making. Furthermore, they are the main instrument for guaranteeing the ‘stay within sets once committed’ principle of SBD by declaring the current DS on which subsystems can experiment and focus.

3.3. MODEL-BASED AND EXPERIMENT-BASED TRADE-OFF CURVES

From the universe of tools and practices supporting the NDP, the ToC are the most referential. They are diagrams demonstrating the contradictory relationship between different project parameters, which affect project decisions (MOHSIN; ABDULATEEF; AL-ASHAAB, 2020). ToC are an instrument for generating, storing, sharing, and managing knowledge during development (LEVANDOWSKI; RAUDBERGET; JOHANESSON, 2014a) and support many filtering activities. By exploring design contradictions, one can compare different solution alternatives and identify those that meet exclusion criteria in SBD (AUTZEN, 2013; FRYE, 2010; MEBANE *et al*., 2011; RAUDBERGET, 2010a; RAUDBERGET, 2010b; RAUDBERGET, 2011). Thus, the learning and experimentation processes found their roots in ToC.

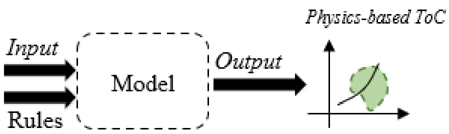
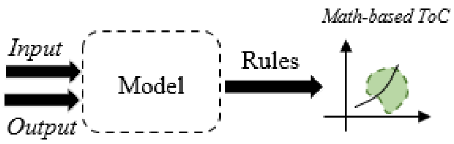
The classification of ToC is a concern in the literature, which considers the source of information used to generate curves (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI; AL-ASHAAB; ALMEIDA, 2021). According to this classification, ToC can be knowledge-based, physics-based, and math-based. Data from real experimentation, such as prototypes, tests, previous knowledge, and analysis of competitors, constitutes knowledge-based ToC (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016b; ARACI *et al*., 2017). When data comes from the physical properties and mechanisms of the product, the ToC are physics-based (ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI; AL-ASHAAB; ALMEIDA, 2021), i.e., representing physics principles, conservation laws, and closure relations.

Math-based ToC are based on mathematical models and computational tools to predict the behaviour of parameters (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI *et al*., 2016b; ARACI *et al*., 2017; ARACI; AL-ASHAAB; ALMEIDA, 2021). Algorithms are employed to establish mathematical and statistical correlations to provide input and output data. The literature criticises Math-based ToC due to its mathematical and statistical nature (ARACI; AL-ASHAAB; MAKSIMOVIC, 2015; ARACI; AL-ASHAAB; MAKSIMOVIC, 2016a; ARACI *et al*., 2017; ARACI; AL-ASHAAB;

ALMEIDA, 2021). The methods for generating ToC in the literature focus on products with a solid knowledge background under the premise that SBD can only be supported by actual data rather than guesswork, wishful thinking, or unreliable sources.

One of the most mentioned and acknowledged hindering factors for SBD is its resource-consuming nature, mostly due to the depth and number of experiments necessary to support decision-making. Development projects, however, are subject to considerable resource restrictions, posing a scenario that may discourage its adoption. Fostering implementation cases of SBD means providing paths to balance resources and experimentation. Computational tools to predict the system behaviour with errors within tolerable ranges are the path to enable the benefits arising from SBD with less experimentation. To better understand the generation of ToC during the NDP, this research proposes a classification based on the transformation of the information that generates the curves. Table 3.1 provides the classification and its correspondence with the current literature.

Table 3.1. Trade-off Curves classification

Classification		Source	Transformation
Proposed	**Current**		
Experiment-based	Knowledge-based	✓ Prototypes; ✓ Tests; ✓ Previous projects; ✓ Competitor products…	Ready-to-use
Model-based	Physics-based	✓ Computational models; ✓ State-of-the-art knowledge…	Through deductive, physics-driven, and white-box models 
	Math-based	✓ Computational models	Through inductive, data-driven, or black-box models 

Source: Oliveira *et al*. (2023a).

Experiment-based ToC are the knowledge-based ToC with data ready-to-use. The Model-based ToC transforms the information through mathematical equations and simulations based on physical principles or statistical learning relations. They are not as reliable as Experiment-based curves and must be validated through tests and prototypes. Nevertheless, it is easier and less expensive to generalise design conditions than perform experiments (OLIVEIRA *et al*. 2023a). Identifying system and subsystem contradictions is an early-stage activity in SBD to understand general design conflicts, restrictions, and interrelations outlining the project. This activity is based on the contradictions identified in the roof of QFD matrices (see Fig. 3.4). Drawing ToC with all contradictions involved in the design may not be possible due to time, human, and financial resource restrictions. In this case, trade-offs are ranked and prioritised according to their impact on the overall performance of the product or subsystem (Oliveira *et al*., 2017).

The role and generation of Experiment-based and Model-based ToC receive emphasis in different stages of the NDP (Fig. 3.6). Designing products means facing several contradictions while managing resources to explore them. Thus, designers prioritise and plan the study of critical parameters relationship according to the number of subsystems involved in the contradiction, the degree of information readiness, and the goals for knowledge gaining at each integration event. System-level contradictions (more than one subsystem involved) are critical since they delimit DS in terms of system-level metrics and provide general guidelines for the product. The effort to understand such contradictions early in the design is justified by their input for narrowing-down alternatives based on the compatibility of subsystems.

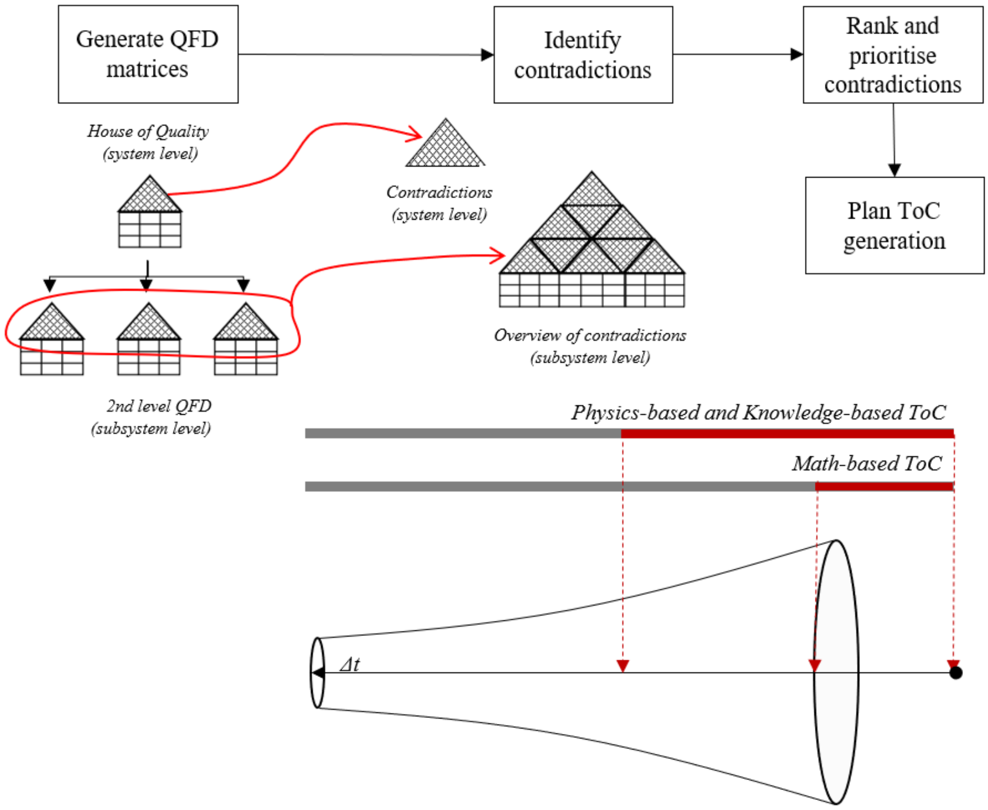
NDP activities demand a higher degree of information basing decisions. Hence, designers seek to gather as much information as possible early in the project, given project restrictions. They allocate efforts initially for generating curves obtained with little workload and experimentation, which includes information from previous projects, competitors, and computational simulations. Another factor influencing the decision regarding ToC generation is development planning. LPD plans define deliveries and knowledge acquisition for each integration event and LC (see section 3.6). Depending on the decisions and milestones planned, ToC can be generated later in the development to attend to resource restrictions. IE act as a pacemaker pulling knowledge during the development

.

3.3.1. Experiment-based trade-off curves

Experiment-based ToC are widely explored in the literature by Araci, Al-Ashaab, and Maksimovic (2015), Araci, Al-Ashaab, and Maksimovic (2016a), Araci *et al*. (2017), and Mohsin, Abdulateef, and Al-Ashaab (2020). Figure 3.7 presents the model for knowledge-based ToC of Araci *et al*. (2017) and Araci *et al*. (2020). Understanding the decision criteria comprises the first step, followed by experiments to collect data and generate the curves. Based on this, the authors include the application of the tool for eliminating concepts and alternatives based on the delimited feasible area.

Figure 3.6. Trade-off Curves generation during Set-Based Design



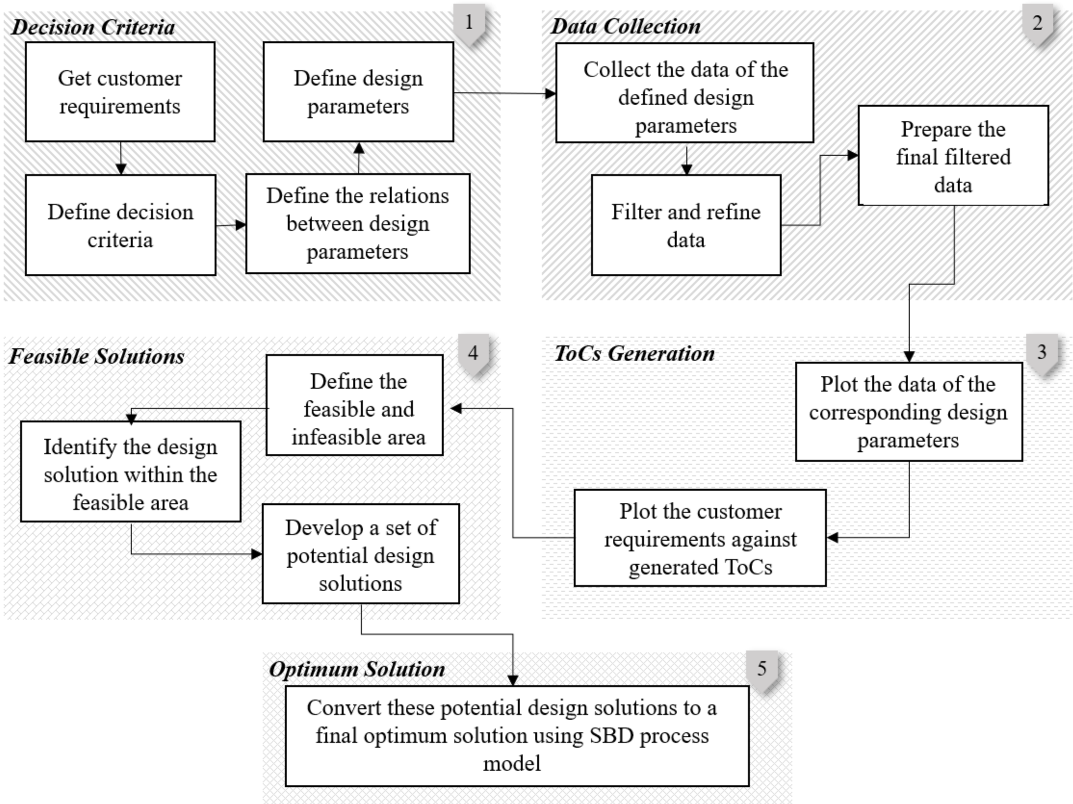
Source: Adapted from Oliveira *et al*. (2023a).

3.3.2. Model-based trade-off curves

Decision-making in SBD is preferably grounded on information coming from materials tests, component experiments, and prototype evaluation. When these characterisations are unviable or impracticable, simulations, computational, and statistical tools assist in product design. The lack of previous experience in developing some products implies larger DS and more resources to explore it. Thus, developers rely on predictions provided by reliable numerical simulations and Machine Learning (ML) models to enable learning about the product.

Emerging technologies are usually not commercially available with consolidated supply chains for their materials and components. It increases manufacturing costs and hinders the development of numerous prototypes and the execution of experiments. Thus, the application of computational tools plays a fundamental role in the design process. Physical and mathematical models provide information regarding processes and phenomena of the system, enable the determination of parameters tendency, the in-depth exploration and filtering of the DS, and the establishment of high-interest design regions.

Figure 3.7. Process for generating Knowledge-based Trade-off Curves

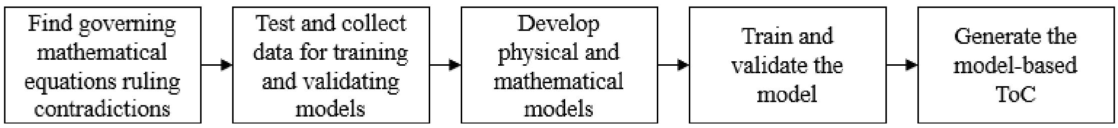


Source: Adapted from Araci *et al*. (2017) and Araci *et al*. (2020).

Figure 3.8 presents the process for generating model-based ToC. The fundaments for generating physics-based ToC lie in the governing equations ruling the product. Initially, designers model the product and the phenomena pertaining to its operation. Based on this, they set assumptions according to the operating point and goals established in the value definition. The objective is to simplify the equations, translating fundamental laws of the system and subsystems (e.g., energy conservation, Maxwell's laws, Navier-Stokes equations) and working conditions. Subsequently, developers determine the governing equations that rule the system operation and properly couple them to grasp the product performance (OLIVEIRA *et al.*, 2023a).

Math-based ToC follow a different path. The volume of data required for training and testing ML models is usually large and expensive. Thus, developers process and analyse the available data to assure viability and adequacy for utilisation. The data reliability is higher when originated in experiments and tests, but data from validated physical models can be employed (OLIVEIRA *et al.*, 2023a). Subsequently, a model fitting the collected data is selected, trained, validated, and tested according to the chosen ML methodology.

Figure 3.8. Process for generating Model-based Trade-off Curves.



Source: Oliveira *et al*. (2023a).

An in-depth understanding of the system operation and its mathematical modelling is fundamental to determining the restrictions, operating, and boundary simulation conditions. System performance metrics, budget, resource constraints, operational limitations of subsystems, and previous design knowledge outline them. Experimental tests to validate, train the models and estimate the deviation of results are crucial. Nevertheless, developing several prototypes for validating governing equations may not be feasible. Thus, decoupling governing equations and evaluating them is a possibility. It is necessary to work within acceptable deviation ranges despite the source of data to generate ToC.

3.4. BALANCING STRATEGIES FOR SET-BASED DESIGN

SBD demands experimentation beyond the project to foster learning instead of focusing on operational efficiency (AMMAR *et al.*, 2017; AMMAR *et al.*, 2018; OLIVEIRA *et al.*, 2022b). This scenario hinders SBD adoption since it requires far more resources to implement than traditional strategies (AUTZEN, 2013; CHAN, 2016; SCHULZE, 2016; PESSOA; TRABASSO, 2017; TOCHE; PELLERIN; FORTIN, 2020; OLIVEIRA *et al*., 2022a; OLIVEIRA *et al*., 2022b). Thus, advancing and fostering SBD means opening avenues for balancing resources and DS size. Three approaches emerge in response to this, which are the CS, the definition of the LI, and controlling the amount and depth of experiments (OLIVEIRA *et al*., 2022a; OLIVEIRA *et al*., 2022b).

CS is one of the most explored fields in SBD and consists in assessing alternatives, concepts, or regions of the DS, removing those with less probability of success supported by quantitative methods (OLIVEIRA *et al*., 2022b). Many works advance in computational tools and techniques to assist in discarding or focusing on regions of DS (LEE, 1996; AVIGAD; MOSHAIOV, 2009; SCHUH; RUDOLF; LUEDTKE, 2016; SCHULZE, 2016; AMINE; PAILHÈS; PERRY, 2017; BERTONI; BERTONI, 2019; MÜLLER; PANAROTTO; ISAKSSON, 2019; SHALLCROSS; PARNELL; POHL, 2020b; SHALLCROSS *et al*., 2021a). Information from previous projects and competing products form the basis for CS (AL-ASHAAB *et al*., 2013; BHUSHAN, 2007; FURIAN *et al*., 2011; KHAN *et al*., 2011; MAKSIMOVIC, 2013; SCHÄFER; SORENSEN, 2010).

CS finds limitations since it requires a solid knowledge background for evaluating possibilities, posing restrictions for its adoption in emerging technologies. Applying CS with a lack of previous knowledge and inexperience is a challenge. The LI was also explored in the literature by a few works (AL-ASHAAB *et al*., 2013; AUTZEN, 2013; AMMAR *et al*., 2018; KHAN *et al*., 2011; MAULANA, 2017). Attributing a LI means removing parts of the product from the NDP (OLIVEIRA *et al*., 2022b). It enables focusing resources on critical subsystems in projects subject to significant restrictions (AL-ASHAAB *et al*., 2013; AMMAR *et al*., 2018; AUTZEN, 2013; KHAN, *et al*. 2011; MAULANA, 2017; PESSOA; TRABASSO, 2017).

The LI creates a hybrid development approach scenario where parts are developed under the SBD umbrella, and parts are designed by PBD precepts (OLIVEIRA *et al*., 2022b). Subsystems are candidates for PBD when grounded in consolidated knowledge, require little or no innovation, and present a wide range of possibilities to meet requirements. They will be Chosen-to-fit (CHTF) when they do not significantly influence system performance or Custom-to-fit (CUTF) for medium or high influence. Subsystems that deliver more value or are riskier are the best candidates for SBD (PESSOA; TRABASSO, 2017).

Works mentioning and proposing activities for the LI approached the subject superficially. Even though they demonstrate the use of diagrams and matrices, they do not provide guidelines to assist in deciding the LI. Furthermore, they do not present the integration of parts in different domains. Oliveira *et al*. (2022a) recommended further advances in models and methods to decide on the LI and the size of the set. They acknowledged the necessity of guidelines to assist the decision regarding hybrid development strategies for a well-established development process.

3.4.1. Hybrid development strategy

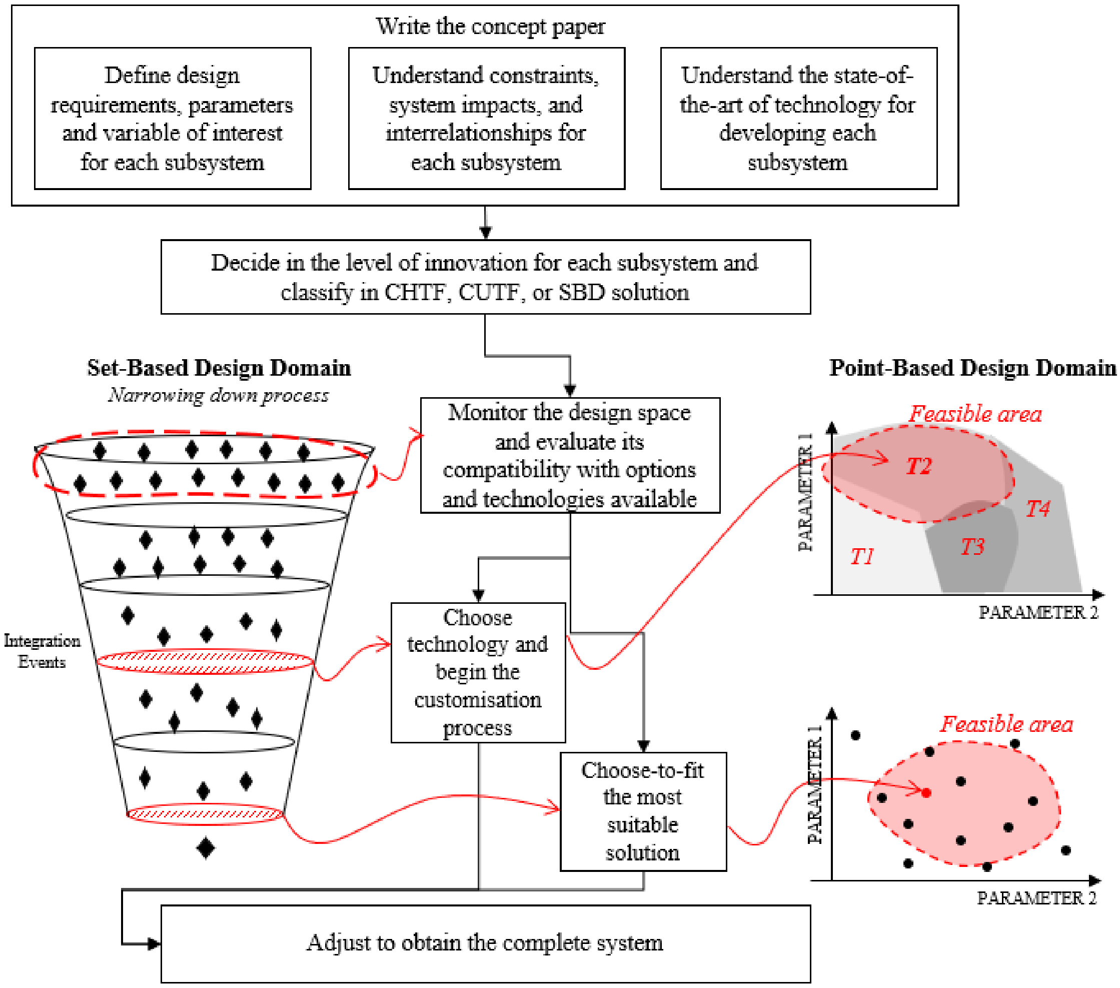
Determining the LI of each part of the product requires a clear value definition and deployment. The main document responsible for this decision is the concept paper. Value deployment evidences the importance, constraints, influence, and impact of each part on the system, indicating the candidates for integrating the SBD or PBD domains. Enhancing the chances of innovating and finding the best solution means prioritising SBD and allocating the higher number of parts possible under its umbrella, considering the availability of resources. The decision on the LI is delimited by the necessity of balancing the DS. Based on this, the criteria for deciding on the LI include the influence on system and subsystems performance, the technological state-of-the-art, design restrictions, and limitations.

The SBD is suitable for parts capable of posing significant impact or subject to severe restrictions since the NDP seeks compatibility between functions and the best overall performance. SBD parts are the core of the product and impact the system in a way that small changes in their design significantly affect performance. They also present intricate relations with other parts regarding performance metrics and geometric and operation restrictions. Subsystems with greater impacts require a higher compatibility degree. The risk of developing such parts in PBD is considerable since only the NDP guarantees the convergence of the system.

Conversely, the candidates for a PBD strategy are parts easily detached from the product, presenting little influence or interference. If the subsystem impacts performance to a certain degree, posing operational, geometrical, or other restrictions, its influence on the overall system determines whether this part is suitable for CUTF or CHTF. The decision regarding the LI also considers technological maturity. Parts with commercially available components fitting design requirements are suitable for PBD. CHTF solutions present a low influence on the system and subsystems, albeit CUTF solutions accommodate higher impacts to seek better overall performance and reduce the restrictions posed in other subsystems.

Figure 3.9 presents the method for defining the LI and conducting a hybrid development strategy based on its results. The LI definition is a Multi-Criteria Sorting Problem (MCSP) in which developers evaluate subsystems according to predefined criteria and sort them into ordinated classes. The problem under consideration is to assign a finite set of n subsystems $S = \{s_1, s_2, \ldots, s_n\}$ into four predefined groups: high, medium, low, or no innovation.

Figure 3.9. Level of Innovation and the Hybrid Development approach.



Source: Oliveira *et al*. (2022b).

Table 3.2 presents a generic innovation matrix in which subsystems are attributed to development strategies according to their class. Subsystems are described using a vector of m criteria G = (g1, g2, ..., gm), starting or limited to the ones presented in this research. They can be expanded to embrace more restrictions and particularities of each project, including uncertainties. Nevertheless, they comprise the main factors that lead to the decision on the LI. Classes are defined through a reference for each LI, i.e., the performance vector describing a referential subsystem included in the class (outranking methods) or delimiting its thresholds (utility methods).

Table 3.2. Innovation matrix.

		s_1	**s_2**	**...**	**s_n**
Criteria	g1: Market availability				
	g2: Technological development				
	g3: Impact on the system		***MCDA evaluation***		
	g4: Impact on subsystems				
	…				
Classes	Level of innovation	high	medium	low	no
Development strategy		**SBD**	**SBD/ CUTF**	**CUTF**	**CHTF**

Source: Oliveira *et al*. (2022b).

Many consolidated sorting methods adhere to the LI definition as Electre-Tri (YU, 1992), Electre-Tri-nC (ALMEIDA-DIAS; FIGUEIRA; ROY, 2012), UTADIS (ZOPOUNIDIS; DOUPOS, 1999), Rough Sets (GRECO; MATARAZZO; SLOWINSKI, 2002), PromSort (ARAZ; OZKARAHAN, 2007), FlowSort (NEMERY; LAMBORAY, 2008), Theseus Method (FERNANDEZ; NAVARRO, 2011), AHPsort (ISHIZAKA; PEARMAN; NEMERY, 2012), DISWOTH (KARASAKAL; CIVELEK, 2020), and MACBETHsort (ISHIZAKA; GORDON, 2016), to name a few.

The MCDA model must be usable with a reasonable effort not to place excessive demands on the decision-makers, as corroborated by Belton and Stewart (2002). Thus, for less complex products with few subsystems and with sufficient knowledge background, developers might be confident in using methods such as AHPsort. Nevertheless, complex product development with many interacting design variables, design teams, and high uncertainty are difficult to make decisions (ZIMMERMANN *et* *al*., 2017). It poses a scenario in which the resolution of the MCSP is not easily left to intuition, and reasons for a robust structured analysis emerge.

The appropriate method can be selected based on previous experience from the team and organisation in MCSP, the number of subsystems, the complexity of the project, and the knowledge background to support the decision. Cinelli *et al*. (2022) developed a tool to assist in the selection of Multi-Criteria Decision Analysis (MCDA) methods by inputting the characteristics of the decision and problem. After the attribution of subsystems to each domain, developers conduct the hybrid development strategy by controlling compatibility.

The NDP converges to a solution later in development which differs from the PBD logic. Hence, the definition of PBD solutions happens only when the NDP results in a DS sufficiently reduced to provide a clear idea of their required performance. Thus, it is crucial to mitigate risks by monitoring the compatibility between available PBD technologies and the current DS of SBD subsystems in each integration event. It enables to react when designers run out of options to fit the SBD domain.

Monitoring the DS concerning customisation possibilities provides the information necessary to develop CUTF solutions. They follow the convergence of SBD performance parameters that affect their customisation process. CUTF solutions must be grounded in well-defined range values of engineering requirements. Its development starts when the knowledge status in the SBD domain provides clear and limited-range performance values for the technology reach. The customisation follows the DS restriction to accommodate operational requirements and enable system coupling.

The dimensional parameters associated with the product are an example. CUTF solutions are selected when dimensions vary little between the design alternatives, providing a clear idea of its requirements. In contrast, CHTF solutions require few adjustments and time to fit the part into the system. Furthermore, the information for choosing the PBD option is available only at the end of the NDP. Thus, the development teams select CHTF solutions only when the SBD alternatives differ little concerning performance and parameters. Following the NDP, the customisation of CUTF solutions and the selection of CHTF ends with the final decisions regarding SBD solutions.

In a hybrid development strategy, the scope of IE includes analysing the status of the DS and its compatibility with the options in the PBD domain. Thus, it is crucial to identify the critical performance parameters connecting them for analysing the relationship between PBD and SBD subsystems. Monitoring DS implies reducing project risks by enabling time to react to unpredicted obstacles and developing both strategies in parallel. Furthermore, it avoids the tendency of committing to a solution in the PDB domain early in the project, posing restrictions to SBD subsystems.

The PBD is applied to enable SBD in an environment where it is not viable to explore the DS due to resource constraints. Thus, the SBD domain leads the way toward the final specification of the product, providing requirements for the PBD domain and not the way around. CS, hybrid development strategies, and controlling the number and depth of experiments are complementary balancing strategies that can be adopted to distribute resources properly during development.

3.5. THE NARROWING-DOWN PROCESS OF SET-BASED DESIGN

The NDP follows the pace set by IE that pull knowledge produced in LC at all levels of the product. This research proposes the TK approach (ROTHER, 2010) to organise and connect development activities, planning, and knowledge creation. Its deployment nature favours the alignment of all development efforts toward the challenge based on the product vision or, in other words, customer value.

3.5.1. The Toyota Kata Approach for Lean Product Development

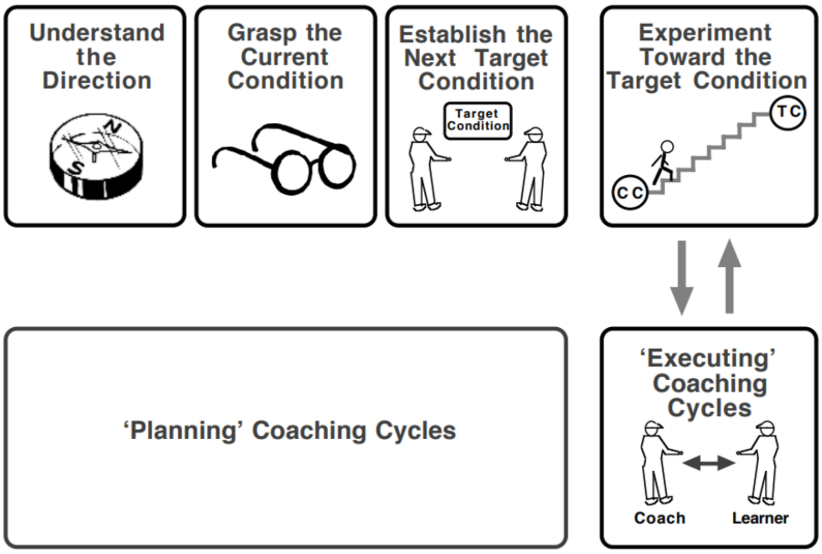
The TK approach was first mentioned by Rother (2010), focusing on improving manufacturing processes. The author made an effort to decode the success of Toyota in managing and improving their manufacturing constantly, a little each day. The model from Rother (2010) represented the first decoding of daily kaizen, enabling daily little improvements toward a desired process performance. The TK approach is a model to manage, lead and develop people through the introduction of routines and habits (ROTHER, 2010). The logic is that through the daily repetition of the PDCA cycle for solving little incremental problems, it is possible to establish a natural mindset of scientifical learning and, consequently, consistently advance to the achievement of the goals. The systematic implementation and execution of TK regularly at all organisational levels leads to an organisation capable of learning based on actual data and solving problems scientifically.

The approach proposed by Rother (2010) consists of two complimentary routines executed by two actors: the Improvement Kata (IK), executed by the apprentice, and the

Coaching Kata (CK), executed by the coach, as presented in Figure 3.10. Practicing these structured routines repeatedly implies forming unconscious and natural behaviour patterns of continuous improvement and scientific thinking (TOVOINEN, 2015). An apprentice is a person that aims to solve problems and improve processes. The coach is a leader or chief with solid knowledge of TK and aims to guide the conduction of IK routines and assist in defining goals and challenges.

The beginning of the IK routine is marked by the establishment of a long-term challenge or direction. This challenge can be assigned by the coach as a performance goal or be established in agreement with the apprentice. Since it is complex to control and manage the achievement of a long-term condition, the TK approach preconises the deployment of the challenge in intermediary Target Conditions (TC) in a shorter time horizon. To define the TC, the apprentice analyses the gap between the CC of the process and the challenge. Once the next TC is set, the apprentice understands what is preventing him to achieve it, defining the obstacles. Through short PCDA cycles, the apprentice overcomes them and achieves the TC leading in the long term to the accomplishment of the challenge.

Figure 3.10. The Toyota Kata for process improvement.



Source: Rother (2015).

The CK routine consists of a questioning pattern from the coach to the apprentice at the end of each PDCA cycle. The coach verifies if the apprentice is following the method and developing the mindset. Thus, he avoids giving answers, stimulates reflection and learning, and assures that the apprentice is following the scientific method. Rother (2010) emphasises rules about the routines, such as the duration of the coaching sessions of no longer than 15 minutes, avoiding discussion beyond the CK scope, adopt physical instead of electronic storyboards, and so on.

The set of rules posed by Rother (2010) does not favour its application in other environments to foster scientifical thinking compatible with lean, such as in R&D projects. Nevertheless, the structure of the TK approach and its routines create an environment capable of integrating and aligning development efforts, connecting IE and LC. Development activities generate a high volume of data, simulations, computer-aided tasks, and design. Representing the results of experiments on a physical board may not be an easy task. Furthermore, discussions regarding product parameters and solution alternatives add considerable value during PDP.

The CE needs to suggest and participate in the technical execution of the project and the presence of other subsystems during coaching sessions promotes integration. This scenario leads to the necessity to adapt and evolve the model of Rother (2010) toward a TK Development (TKDev) approach to support the LPD (Table 3.3). The learning orientation required by SBD finds room in the TKDev practices and routines. The decodification of the way Toyota conducts its activities by the author is the procedure the company uses in product development as well. Instead of focusing on learning to eliminate waste, TKDev focuses on learning to deliver maximum value through the design of solutions for customers.

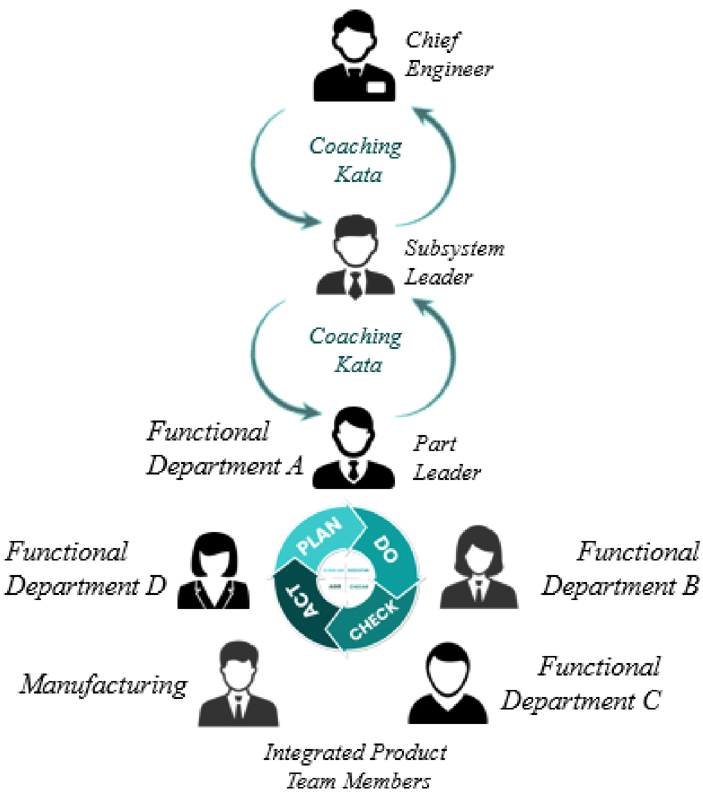
Table 3.3. Differences between Toyota Kata improvement and development.

	TK improvement	***TK development***
Duration	*Max. 15 minutes*	*As long as necessary*
Discussion beyond five questions	*No*	*Yes*
Coach interference	*No*	*Yes*
Participants	*Only coach and apprentice*	*Coach, apprentice and others*
Storyboard	*Physical board*	*Physical or electronic board*
Frequency	*Daily*	*Daily, weekly, or biweekly*
Scope	*Process improvement*	*Development*
Challenge establishment	*Coach or coach and apprentice*	*Coach*

In a development environment, the CE and parts leadership play the role of Coach (Fig. 3.11). They observe if their apprentices are following scientifical thinking to learn and gather information to support decision-making. They encourage them to experiment beyond what will be applied in the product to expand knowledge in the organisation and enhance the chances of innovating. Furthermore, they assure that apprentices are focused on customer value and understand their contribution to it, considering only alternatives inside the DS agreed upon in the last integration event. Structuring LC and IE under the TKDev umbrella is a path to the 'stay within sets once committed' principle of SBD.

The TKDev follows the logic of the TK approach as proposed by Rother (2010) (Fig. 3.12). A challenge is set to all product levels deployed from the product vision, i.e., the customer value defined in the concept paper. It represents a declaration of the required performance the part must deliver to the product to achieve development goals. It describes the operation, performance, cost, design, usability, and other ECC of the parts that will enable them to provide what is expected. Once clear challenges are set, parts iterate through short PDCA cycles toward value, experimenting, discovering, and learning along the process.

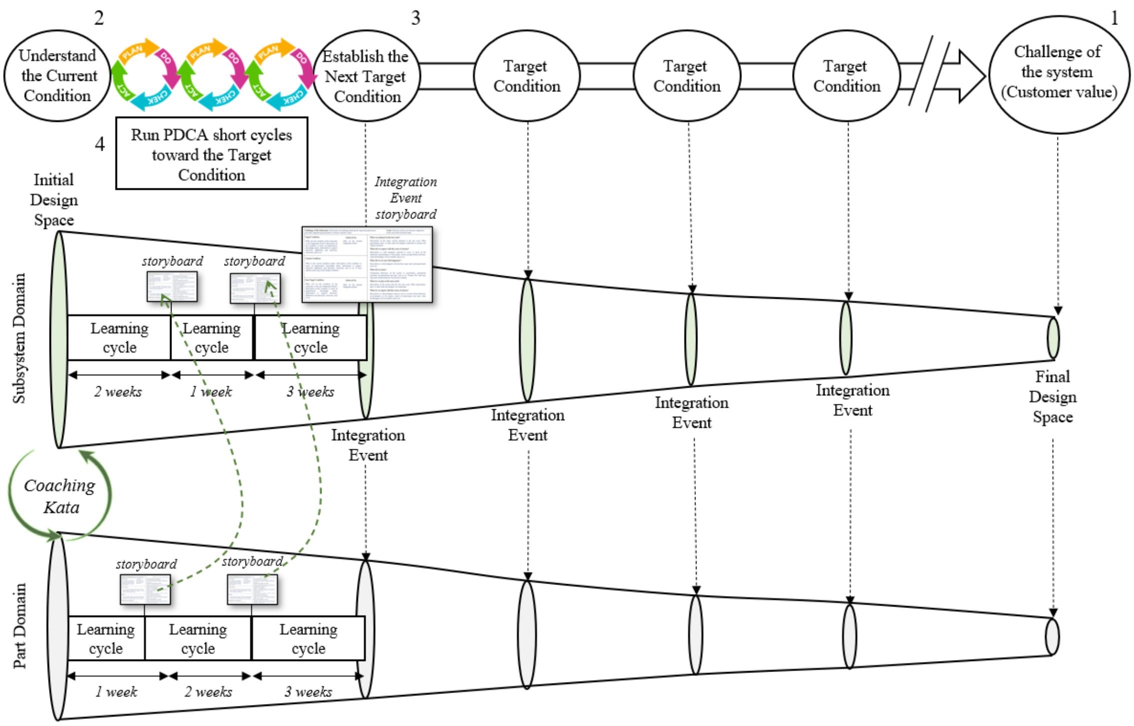
Figure 3.11. TKDev value deployment.



Initially, the apprentice understands the CC of the project concerning the challenge, describing what is known, what is unknown, how it affects the development, and the resources available at the moment. Based on this, the apprentice sets an intermediary TC corresponding to the information expected to be acquired to input the next integration event. Subsequently, he identifies the obstacles preventing him to achieve the TC and starts to conduct short LC aiming to overcome them. After this process, the parts provide the information necessary to narrow the DS during the next integration event. The CK happens between LC based on the storyboard, as presented in Figure 3.13.

The apprentice fills the storyboard with information on the activities and experimentation results performed during the cycle, registering what was learned. The storyboard will serve as a knowledge registration tool, declaring the interpretation of experiments results summarised in the learning field of the storyboard. It will contain behaviour and relation of parameters, failure points of materials and structures, simulation results and validation, procedures and their outcomes, successful attempts and failures, insights on new products or solutions, recommendation of information sources, and so on.

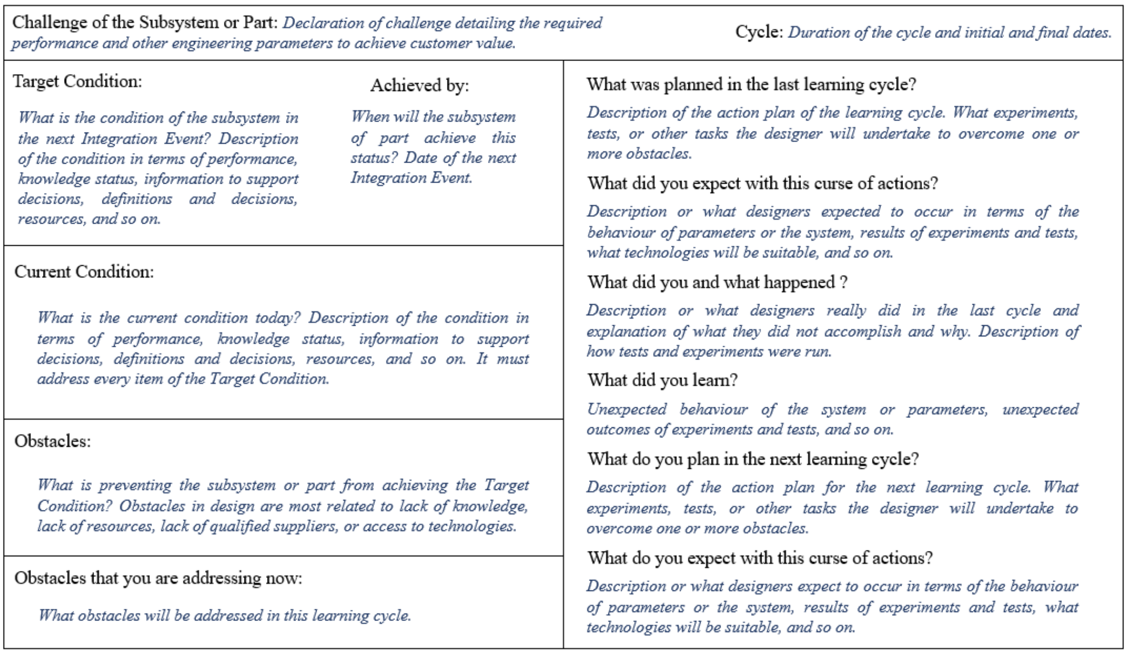
Figure 3.12. TKDev approach.



3.5.2. *Integration Events and the Narrowing down Process*

IE serve as a pacemaker, pulling knowledge, decisions, prototypes, milestones, and major deliveries. They relate to LC at all levels of the product and with every integrated product team since TC describe what is required to achieve the goals set for the event. Parts and subsystems present their learning and outcome from tests to share knowledge with peers and suggest a new reduced DS to be considered after the event. The knowledge status is compared and consolidated, and the new DS is agreed upon, which is the major outcome of every integration event. The succession of several events paces the NDP until a final solution or a very small set of alternatives is obtained.

Figure 3.13. TKDev learning cycle storyboard.



The structure of the integration event follows the logic of the storyboard, as presented in Figure 3.14. In the meeting, every subsystem presents its board, showing what was done in the last LC. Learning and results are highlighted and shared. At the end, the updated DS from the subsystem perspective is presented. The participation of manufacturing during the event is marked by its storyboard, gathering knowledge status concerning industrialisation and application of the alternatives considered in the DS.

Other stakeholders can be present as well to validate and input information during the NDP.

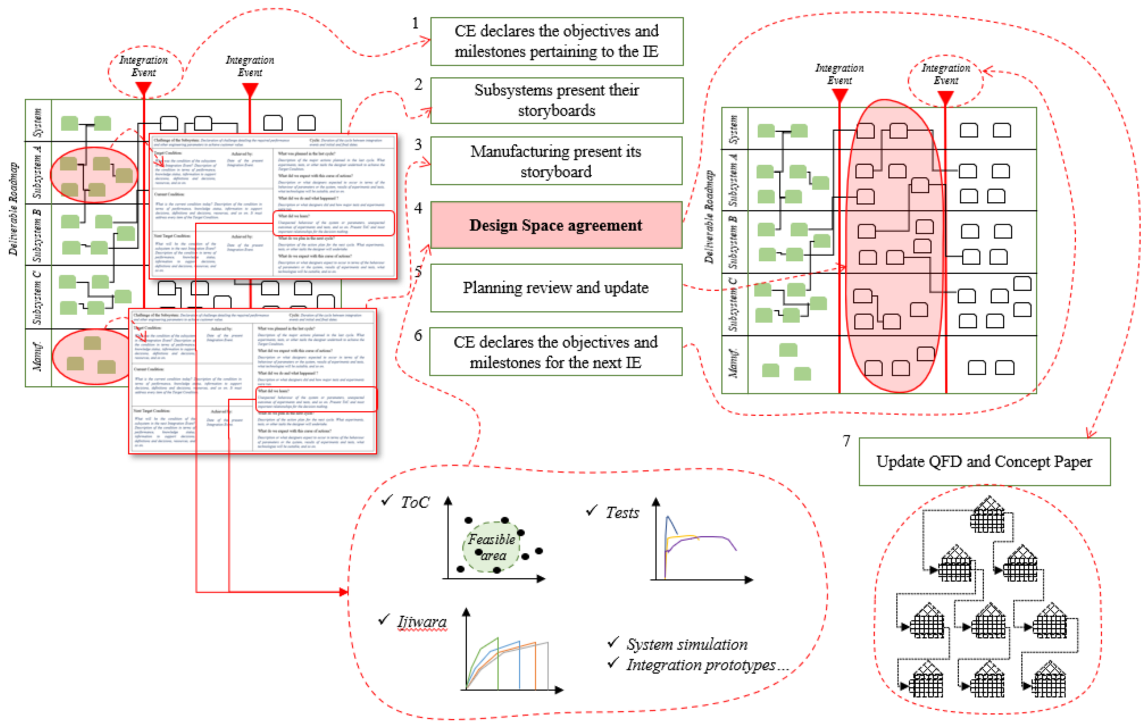
Figure 3.14. TKDev integration event storyboard.

<table>
<tr><td colspan="2">Challenge of the Subsystem: Declaration of challenge detailing the required performance and other engineering parameters to achieve customer value.</td><td>Cycle: Duration of the cycle between integration events and initial and final dates.</td></tr>
<tr><td>Target Condition:
What was the condition of the subsystem in the Integration Event? Description of the condition in terms of performance, knowledge status, information to support decisions, definitions and decisions, resources, and so on.</td><td>Achieved by:
Date of the present Integration Event.</td><td rowspan="3">What was planned in the last cycle?
Description of the major actions planned in the last cycle. What experiments, tests, or other tasks the designer undertook to achieve the Target Condition.
What did we expect with this curse of actions?
Description or what designers expected to occur in terms of the behaviour of parameters or the system, results of experiments and tests, what technologies will be suitable, and so on.
What did we do and what happened ?
Description or what designers did and how major tests and experiments were run.
What did we learn?
Unexpected behaviour of the system or parameters, unexpected outcomes of experiments and tests, and so on. Present ToC and most important relationships for the decision making.
What do we plan in the next cycle?
Description of the action plan for the next cycle. What experiments, tests, or other tasks the designer will undertake.
What do we expect with this curse of actions?
Description or what designers expect to occur in terms of the behaviour of parameters or the system, results of experiments and tests, what technologies will be suitable, and so on.</td></tr>
<tr><td colspan="2">Current Condition:
What is the current condition today? Description of the condition in terms of performance, knowledge status, information to support decisions, definitions and decisions, resources, and so on. It must address every item of the Target Condition.</td></tr>
<tr><td>Next Target Condition:
What will be the condition of the subsystem in the next Integration Event? Description of the condition in terms of performance, knowledge status, information to support decisions, definitions and decisions, resources, and so on.</td><td>Achieved by:
Date of the present Integration Event.</td></tr>
</table>

Figure 3.15 presents the basic structure of an integration event. First, the CE declares the challenge and goals for the integration event. This is previously defined in the DR (see section 3.6). In the sequence, subsystems present their storyboards followed by manufacturing. The storyboards contain ToC, failure tests, and all experimentation, simulation, and prototyping, along with a comparison to the competitor's technology and products. In the case of manufacturing, mock-ups, experiments, technological thresholds, and supplier issues are presented.

Based on this, designers agree on what alternatives and DS regions will be discarded and update the plan for the next integration event. Finally, after the event, leaders update the QFD and the concept paper to include new critical knowledge, lessons learned, and the current DS. The storyboards from IE and LC store important information opening an avenue for a structured way to present, discuss, and share knowledge for all teams and product levels. It standardises the manner information is registered and assures that every cycle is documented, especially what was learned. It loads future projects not only with results but also with insights of engineers about the results.

Figure 3.15. Basic Structure of an Integration Event.



3.6. PLANNING FOR LEAN PRODUCT DEVELOPMENT

The management approach of lean thinking is RBM. It consists of leadership attributing responsibilities and controlling deliveries and results, in opposition to Task-Based Management (TBM) approaches. When attributing activities, people tend to focus on completing tasks and forget about the effect those tasks provoke on the system performance and if they are leading to goal achievement. Furthermore, when leadership assigns actions, it takes the opportunity for people to learn and discover, observing cause-effect relations in experiments toward a result or delivery. Based on this, planning in LPD is underpinned by deploying the challenge in milestones, major and minor deliveries, knowledge and system status, and other quantifiable results.

The logic is that the person responsible for the delivery has the right to plan the activities that will lead to accomplishing the goal. Table 3.4 describes the difference between RBM and TBM. The most important tool in RBM is the DR. It visually represents every delivery, milestone, critical result, goal, and responsibility. Deliveries are distributed over time, following the required precision of the plan. Lean planning recognises the limitations on how accurate a plan can be as the time horizon goes over the long term, so planning detail varies by time horizon. Thus, for the short term, planning is done by days, weeks, or fortnights, for the medium term by months, bimonthly, and in the long term, by semesters or even years.

Table 3.4. Differences between Responsibility-Based Management and Task-Based Management.

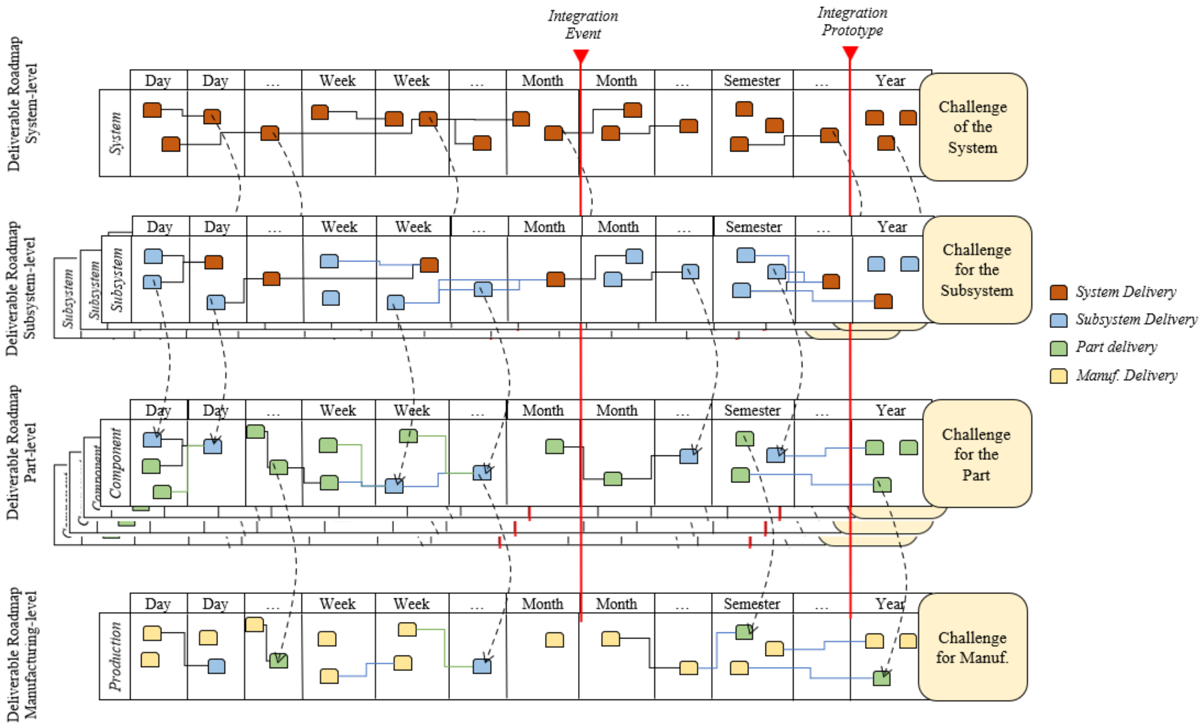
TBM	***RBM***
Task-oriented	*Result-oriented*
What you do > How you do	*How you do > What you do*
Foster execution	*Foster learning*
Focus on accomplish tasks over time	*Focus on learning and monitor the system*
Action plans and Gantt	*DR and PDCA cycles*
Leadership based on authority	*Leadership based on coaching*

The vertical lanes represent the considered time intervals and the horizontal lanes mark the responsibility for deliveries. In this way, it is easy to visualise the progress of deliveries, the status of knowledge, and the interconnection between parts of the product in terms of experiments and relationships. Furthermore, the deployment of deliveries from the system to the subsystems makes it possible to synchronise experimentation between the various levels of the product to deliver what is expected in each integration event.

Figure 3.16 shows the DR of the system, whose responsibility lies with the EC. Initially, he defines and states the challenge, describing how the product must operate to deliver value to the customer. Respecting the project deadline, he breaks the challenge into major deliveries and distributes them appropriately and sequentially over time within the horizontal lanes. After that, the CE and his team, break the major deliveries into packages of smaller deliveries, distributing them in time and assigning responsibility to a level below, i.e., subsystems.

The leader of each subsystem analyses its deliverables and break them down into even smaller packages and assign them to the various parts of the subsystem. This logic is done down to the lowest level of the product. Additionally, IPT members representing manufacturing design their own DR based on the DR of the system, subsystems, and components, marking their responsibilities to ensure the manufacturability and viability of the solutions and DS.

Figure 3.16. Deliverable Roadmaps and the product levels.



The CE assigns deliveries addressing the IE along the NDP, describing decisions and knowledge to be acquired in each event. This will pull ToC and other analyses, experiments, and simulations. As an example, when the CE assigns for an IE a decision regarding what materials are considered for the structure of a determined subsystem, this will pull failure tests, ToC demonstrating performance and cost, investigation of new materials and opportunities, competitors' products analysis, and previous projects knowledge consultation. Based on this, the subsystem can present in the IE the facts that lead to discarding some materials and consider a smaller set of solutions to compose the subsystem.

3.7. FINAL CONSIDERATIONS

This chapter presented the proposed model and process for SBD, developed from a processual perspective, considering inputs, outputs, and transformation process. In this research, the orchestration of resources and people for SBD is based on PDCA cycles organised through the TK approach for development (TKDev) and supported by several tools and methodologies. The gaps and opportunities for advancing knowledge and disseminating SBD identified in the previous Chapter were addressed in this Chapter as presented in Table 3.5.

Table 3.5. Filling the managerial gaps in SBD literature.

Gaps	Contribution of this research
Demonstrate the contribution of value deployment for the NDP	The QFD and the upward and downward propagation of the DS.
Demonstrate the generation and contribution of ToC during the NDP in the context of IE and LC	Model-based ToC generation and their connection with the IE and LC.
Demonstrate how LC and IE are connected and present a method for integrating them	DR, TKDev structure, and storyboards connecting LC and IE.
Present a method for LC and IE management and execution	DR, TKDev structure, and storyboards connecting LC and IE.
Methods to decide on the LI of each part	MCSP and method to integrate CHTF and CUTF solutions with the NDP.
Present a hybrid development strategy model integrating SBD and PBD	Hybrid development strategy and the method to integrate CHTF and CUTF solutions with the NDP.
Approach the participation of stakeholders and manufacturing in the NDP	The QFD, the upward and downward propagation of the DS, the manufacturing DR, and the basic structure of the integration event.
Presenting techniques to support decision-making regarding balancing DS with the resources available	Model-based ToC and hybrid development strategy.
Model the knowledge capture, management, and storage in SBD	TKDev and storyboards.
Present a comprehensive model for the product development flow in SBD	TKDev, DR, IE, and LC.

This model and process for SBD organised and advanced knowledge for managing efforts and resources. This contribution paves the way for including and developing quantitative models and modelling decision-making to further stimulate SBD adoption.

The most critical aspects perceived during the process of creating this model and process are treating and exploring value through QFD, including manufacturing issues. As said before, the most acknowledged hindering factor for SBD is the complexity of balancing resources and DS. Thus, fostering implementation cases of SBD means providing paths to balance resources and experimentation.

This research made two major contributions addressing this problem to what concern a managerial perspective. Including and reinforcing the benefits of Model-based ToC against the contrary movement of the literature in condemning such practices and the pioneer effort to bring the LI to a higher extent to a hybrid development model. Combining these two efforts with the consolidated CS techniques can raise successful SBD implementation cases. This research is also a pioneer in coining the RBM in LPD environments.

CHAPTER 4

THE LEAN DEVELOPMENT OF MAGNETIC REFRIGERATION PRODUCTS

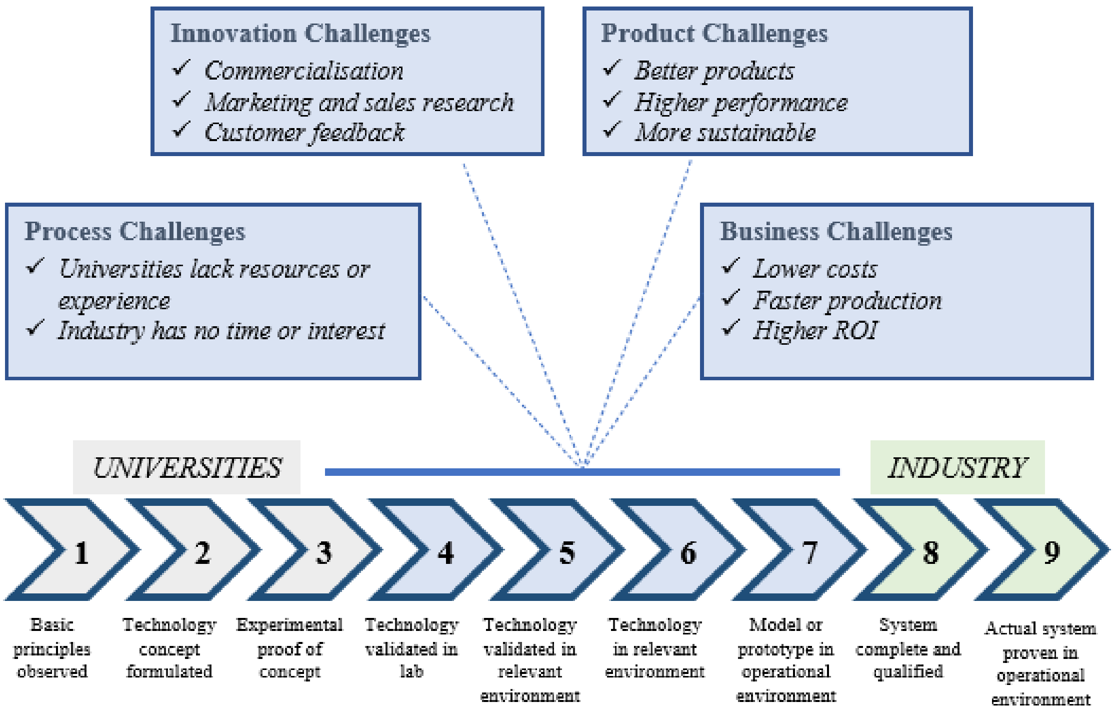
This Chapter describes the managerial model and process for SBD in highly innovative products. It represents not only a pioneer attempt to model the entire SBD management but, also, the first documented case of new technology design under the LPD umbrella. This Doctoral Dissertation is the concretisation of seven years of research, establishing and advancing frontiers to organise product development toward value and learning. The case is presented following the logic proposed in Chapter 3 to enable the reader to understand the correspondence with the topics of the model and process.

Seven sections compose this Chapter. Section 1 introduces and outlines the research environment and technology, aiming to prepare and guide the reader to understand the subsequent sections. Section 2 presents the efforts for value definition and demonstrates the deployment of SBD subsystems from the system to manufacturing levels. Section 3 presents the generation of model-based ToC. Section 4 details the hybrid development strategy and the LI definition. Section 5 discusses planning activities. Finally, section 6 provides highlights about the development flow in SBD, and the TKDev applied to the design.

4.1. THE DEVELOPMENT OF TRL-6 MAGNETIC REFRIGERATION PRODUCTS

Contextualising this case requires providing a clear overview of what means to design a TRL-6 product. TRL is a method for measuring the maturity level of a particular technology, originated in NASA, based on a scale from 1 to 9, as presented in Figure 4.1. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the progress of projects. The term 'Valley of Death' emerged due to the frequent negligence in addressing levels 4 to 7, where neither academia nor the private sector prioritise investment. Consequently, many technologies, albeit promising, finish their maturity journey before deployment. To bridge this valley, collaborative efforts are required.

Figure 4.1. Overview of activities at different technology readiness levels.



Source: Adapted from Hensen *et al.* (2015)

This Doctoral Research was undertaken in this collaborative scenario, where industry and academia gather efforts and resources to advance a new technology toward a TRL-6 level, at which it is demonstrated in a controlled environment considering its operation and size (compactness). Most refrigeration systems utilise vapor-compression technology contributing to 7.8% of global greenhouse gas emissions (KITANOWSKI, 2020). Hence, substantial effort is being invested in the search for alternative refrigerants. The importance of this theme is such that if the energy efficiencies of refrigeration systems are not improved, the electricity consumption in the world could triple by 2050 (KITANOWSKI, 2020).

Magnetic Refrigeration (MR) consists in a technology that produces cold based on the MCE, which is the thermal response of some materials when subjected to a magnetic field variation (PEIXER, 2020; OLIVEIRA *et al,.* 2023a). MR emerges as a promising technology due to three main factors (PEIXER, 2020): (i) less environmental impact since it is not based on harmful gases; (ii) the reversibility of the MCE and other possibilities offer the potential to deliver high efficiency; and (iii) recyclability of fundamental components, such as magnets.

The MR state-of-the-art consists of TRL-5 prototypes, experimentally validated mathematical models, and analysis of design parameters (OLIVEIRA *et al*., 2023a). The literature studies key components and systems composing MR products by analysing single or few operating and geometric conditions, departing farther from what is necessary to design a full TRL-6 operating system. There is no comprehensive and consolidated methodology for their design since the several dependent and deeply coupled variables for each subsystem lead to a complex and intricate design process (OLIVEIRA *et al*., 2023a).

PoloMag is a group created in 2007 for advancing research in the field of MR. The group is held by POLO, a Brazilian research group of the National Institute of Science and Technology in Refrigeration and Thermophysics (INCT - POLO). The objective is to develop MR products overcoming the knowledge and financial barriers through a symbiotic collaboration with private industries and governmental support. The group is recognised as one of the major references in MR in the world with more than 100 publications in Journals and Conferences and developed five prototypes.

The duality between academic production and product development is intrinsic in the group, leading to the necessity of balancing the interest of researchers and sponsors. PoloMag is guided by a general professor advisor, who provides technical support for each project and advises the academic production of all members. The CE assists in the academic advising process and manages product development projects. The group also has an integration engineer to guarantee integration and global optimum due to the intricate character of project parameters between subsystems. Table 4.1 presents the roles and functions in PoloMag related to the product pertaining to this Doctoral Research.

Table 4.1. Integrated product teams and leadership

Subsystem/ Responsibility	Function	Team/Responsible
AMR	Houses the MCM and produces the temperature variation required to operate the system	→ A mechanical engineer (leader); → An undergraduate student in mechanical engineering; → A materials specialist with doctorate in materials engineering.
MC	Provide the magnetic field to generate the MCE in the MCM	→ A mechanical engineer with doctorate in MC for MR (leader); → An undergraduate student in electrical engineering; → A professor in electrical engineering specialist in electromagnetism.
HEx	Thermal interaction between the system and the thermal reservoirs	→ A mechanical engineer with master's degree in MR.
HS	Manage the fluid flow	→ Two undergraduate students in mechanical engineering.
Control system	Synchronisation of magnetisation cycles and fluid flow according to the AMR cycle	→ A control and automation engineer.
Transmission system	Rotate the MC to enable magnetisation and demagnetisation of the MCM	→ An undergraduate student in mechanical engineering; → A specialist mechanical technician.
Integration and manufacturing engineer	Guarantee the global optimal exploring the DS from a system perspective	→ Mechanical engineer with master's degree in MR
CE	Align development efforts toward project goals	→ Post-doctoral student in MR
Project Coordinator	Provide technical support for design issues	→ Professor specialist in MR

Since its creation, the group was having difficulties managing development activities based on traditional management techniques and product development methodologies based on PBD. The novelty of the technology and the very little knowledge background to support decisions made it complex to choose and commit to one single solution in the early development stages. Furthermore, subsystems must be perfectly synchronised to deliver the maximal performance, which requires synchronising activities, establishing a pace for knowledge creation, fostering communication and knowledge sharing, and avoiding focusing on optimum local. Given the novelty and complexity of the technology and application, there are also issues with the scarcity of suppliers. Hence, getting components for testing and even building a prototype is a challenge that takes months to be completed (OLIVEIRA *et al*, 2023b).

One of the major challenges of PoloMag is to execute projects with limited financial and human resources, considering the high cost of the raw materials composing the products and the scarcity of experts in MR. This scenario was not favoured by the management tools and the PBD techniques. The CE adopted Gantt charts to plan and control activities and struggled to synchronise teams based on them. Furthermore, he had difficulties understanding the CC of the project and was unsure if the teams were aligned and able to integrate their solutions later in the development process.

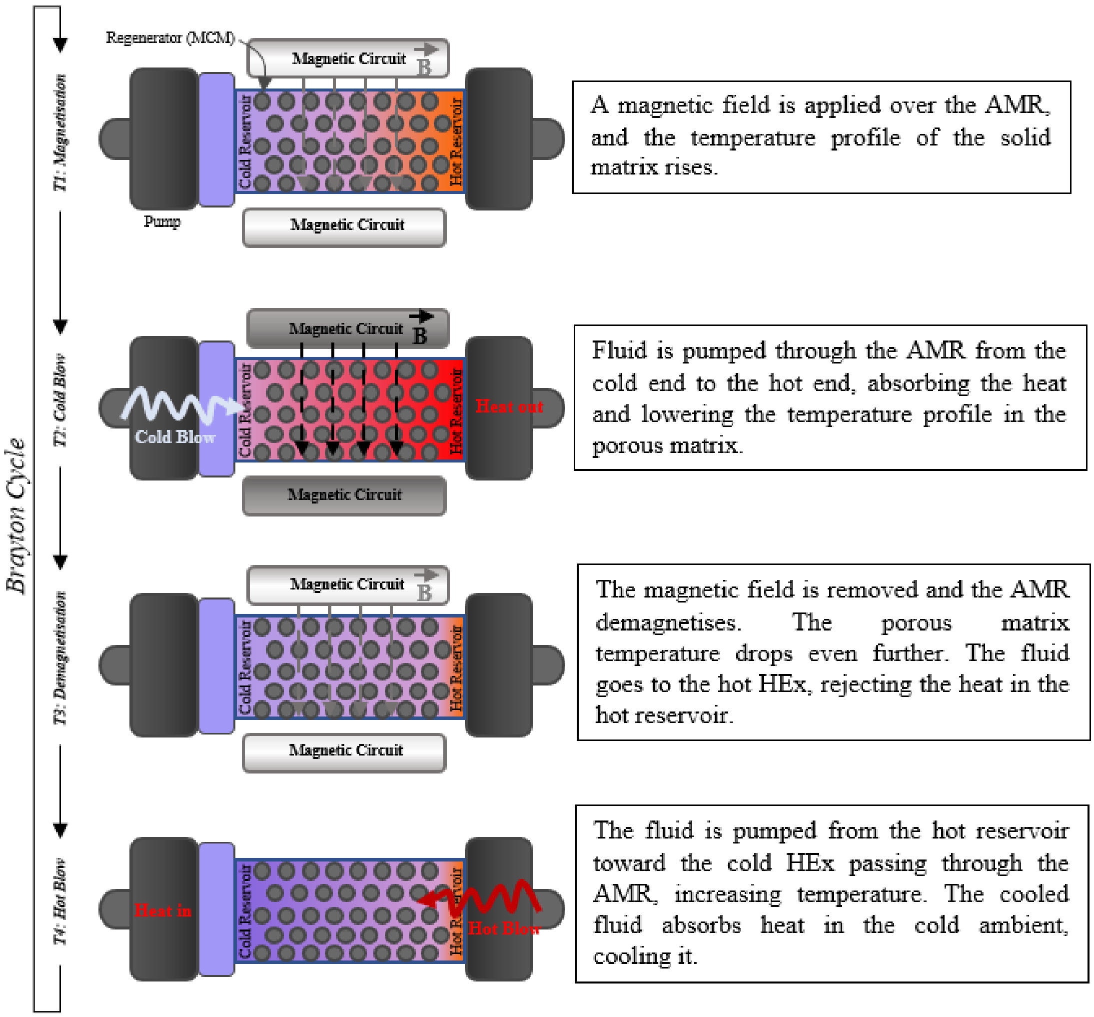
Motivated by difficulties in integrating and managing development, the research group began the implementation of LPD in 2016 in a pilot project of a TRL-6 magnetic winecooler. The results of this project are reported in the Master's Thesis preceding this Dissertation (see OLIVEIRA, 2017). LPD represented a revolution for the research group. Instead of conducting one general meeting once a month or every two months, the group started to pace and cadence design activities by running short PDCA LC and IE assisted by an adaptation of the TK approach. Furthermore, for the first time, a consistent effort to define and understand value through QFD matrices and the introduction of RBM led the group to overcome the obstacles to developing the product.

Underpinning this Doctoral Research are the lessons learned and insights from the pilot project and a comprehensive literature scan showing that SBD is the most unexplored field in LPD. The researcher observed and interacted with the application environment for seven years collecting data and improving LPD initiatives. The projects held by PoloMag require a precise synchronisation and integration of deliveries, a learning-oriented development process to learn about the technology from scratch, and a total alignment toward value to decrease risks while seeking innovation. Technological tendencies and private sector investments led the group to Project MagChill, which aims to develop an air conditioner operated by an MRU, which is a TRL-6 level one-of-a-kind prototype.

The main parts composing the product are (i) the AMR, (ii) the MC, (iii) the HS, and (iv) the HEx (NAKASHIMA *et al.*, 2022; PEIXER *et al*., 2022b; PEIXER *et al.*, 2023). The product also has control and transmission systems responding to the operation of the main parts. The AMR consists in a porous matrix of Magnetocaloric Materials

(MCM) that generates a cooling capacity when subject to magnetisation and demagnetisation through the magnetic field provided by the MC. The HEx are responsible for the thermal contact between the working fluid and the thermal reservoirs, while the HS synchronises the fluid flow with the magnetic field profiles. The synchronisation of the MR parts is mandatory for an efficient operation, which is a thermodynamic cycle of four steps (Fig. 4.2).

Figure 4.2. Idealised thermo-magnetic regenerative Brayton cycle.



Source: Adapted from Trevizoli (2015)

The MRU is a highly innovative product because it is a one-of-a-kind air conditioning application. Even though there are several research groups at the academic level, they have not previously worked with prototypes performing at points of operation like the ones required by an air conditioner application, which limits the use of prior knowledge in the project. Thus, the lack of knowledge of the ranges of values that project parameters would assume arose as a significant challenge, especially in the early stages. Furthermore, the limited project budget and the high cost of raw materials made it unfeasible to build several prototypes and tests.

Computational tools to assist development and planning experimentation to suit the budget and time were crucial to developing the product. It enabled the design team to verify the expected behaviour of processes and components under determined conditions, providing the required information to focus experimentation on strategic points of the project. Integrated Product Teams (IPT) were formed to develop subsystems, and value was deployed to each subsystem to deliver the expected product performance. Integrative development of subsystems is especially important since the product will only reach the required performance if all subsystems work synchronously.

R&D projects are information sensitive and subject to severe confidentiality agreements and protected patents. The application case of this Doctoral Dissertation is not different. An effort was made to provide enough information to demonstrate the benefits and potential of the SBD and LPD while not revealing strategic R&D information. For this reason, simplified and reduced images were provided in this Chapter.

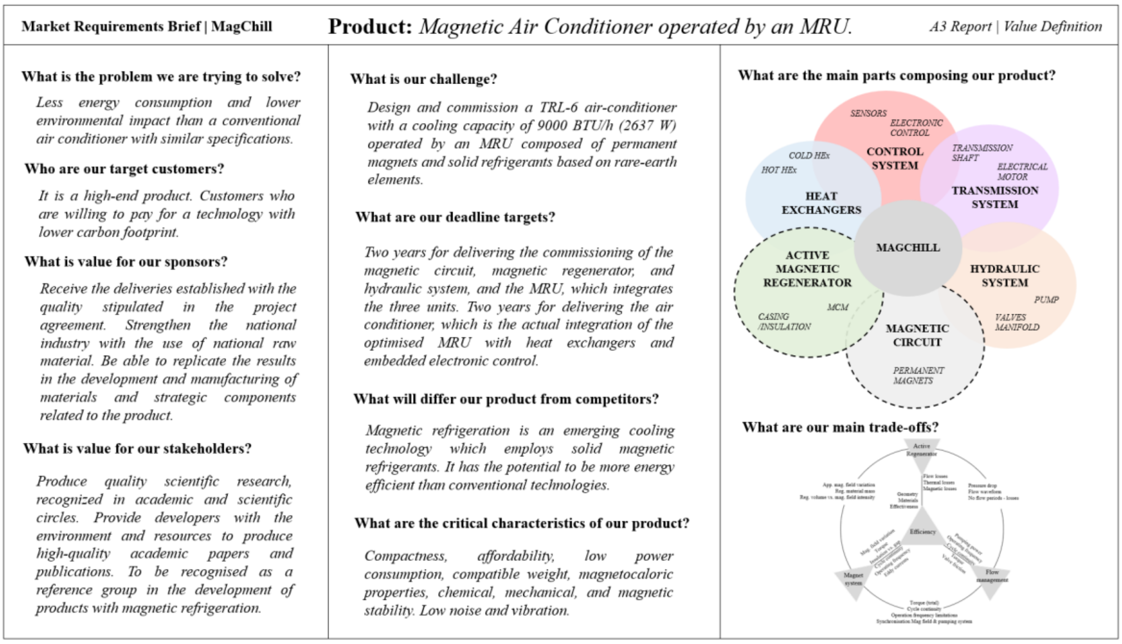
4.2. DEFINING AND DEPLOYING VALUE FOR THE MAGNETIC REFRIGERATION UNIT

Defining value for TRL-6 products based on new technologies is a challenge. The absence of similar technology competitors and the lack of knowledge regarding the potential and operation limitations of the product creates a scenario where designers are not certain about the possible outcomes of the development process. In a highly innovative project, teams have no idea of the final values system parameters will assume to deliver CR. The experimentation and discovery process occurs bringing insight into the technology and ground decision-making in all subsystems concurrently. It is necessary to establish a clear goal for the system and clarify the contribution of each part for it to ensure cohesion and compatibility between efforts.

The project motivation for sponsors is to promote a viable application of specific rare earth elements, aiming to stimulate demand in the future. It implies that the product must at least operate at an equivalent level of a conventional air conditioner. Hence, the main source of information for value definition is the norm in effect for air conditioning in the market (ISO 5151 Standard: ISO 2017) and competitor technologies. The standard cooling capacity rating conditions for moderate climates are 26.7∘C (cold) and 35∘C (hot), and relative humidity of 47% and 40% in cold and hot environments (reservoirs), respectively (PEIXER, 2020).

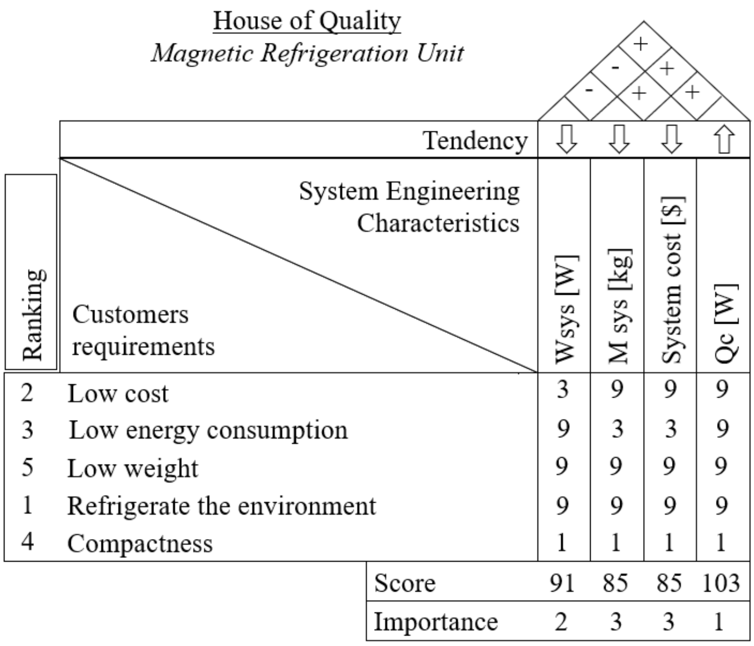
A brief value definition is summarised in the market requirements brief, as presented in Figure 4.3. Additionally, the CE declared the challenge for the product: **design and commission a TRL-6 air-conditioner with a cooling capacity of 9000 BTU/h (2637 W) operated by an MRU composed of permanent magnets and solid refrigerants based on rare-earth elements** (PEIXER *et al.,* 2023). Understanding the context of the project, researching standards, and competitors provide information for the QFD matrices. The concept paper of the product is an expansion of the market requirements brief and the QFD.

Figure 4.3. Simplified market requirements brief for the MRU.



The QFD supports the value deployment activities. Figure 4.4 presents a simplified version of the house of quality for the MRU. A competitive technology for air conditioning can refrigerate the environment, be affordable, consume low energy, have a compatible size with the market, and present an appropriate weight. Based on this, two EC emerge as the most important, i.e., the cooling capacity and the power consumption, which must be analogous to or even better than conventional technologies. The standard cooling capacity rating conditions (PEIXER *et al*., 2023) served as an input for defining range target values for the EC. Analogously, a comparison of conventional air conditioners guided the establishment of the initial DS for power consumption.

Figure 4.4. Simplified house of quality for the MRU.

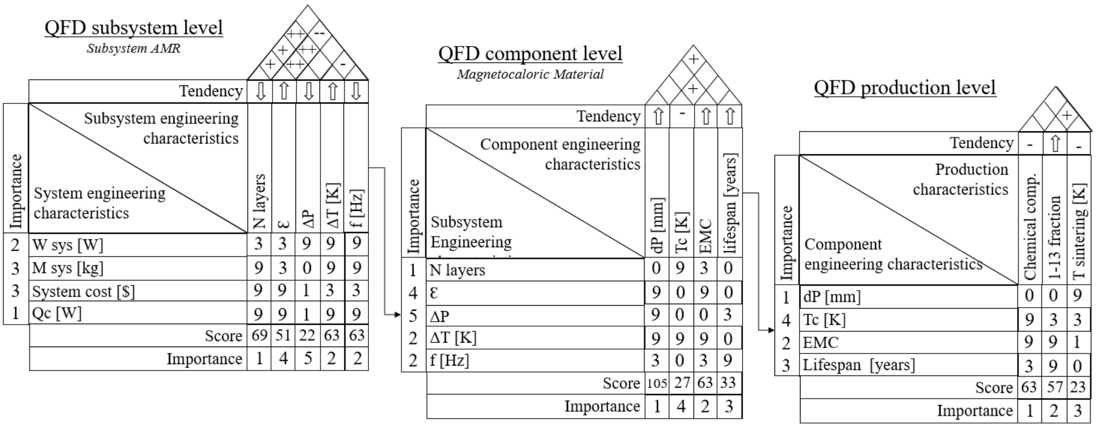


Source: Oliveira *et al*. (2023b)

Many trade-offs arise from the intricate subsystems' relations. Nevertheless, three system parameters emerge as the most critical contradictions: cooling capacity, power consumption, and system cost. The first contradiction is that higher cooling capacities imply increasing the magnetic flux density or refrigerant mass and heat transfer area. It leads to an increase in Permanent Magnets and MCM masses, which are the most expensive materials of the product. The second contradiction is that more refrigeration power implies more energy consumption due to an intensification of the operation frequency and mass flow rate. It results in a rise in dissipation losses for the fluid flow and mechanical transmission.

Due to resource constraints and the aim to enable SBD, the team conducted a hybrid development approach by which the AMR and MC were designed under the SBD domain and the HS and HEx under the PBD domain (see section 4.4). Figures 4.5 and 4.6 present three QFD levels comprising AMR and MC, respectively. The AMR is the main subsystem of the product and works synchronously with the MC aiming to generate cooling capacity at a proper temperature span by a combination of thermodynamic cycles and heat transport through a working fluid (TREVIZOLI *et al.*, 2017). From the second level matrix, we can identify the EC impacting the system to a higher degree, which are the number of layers (N layers), followed by the temperature variation (ΔT) and the operation frequency (f).

Figure 4.5. Simplified deployment for the AMR, MMC, and its production.

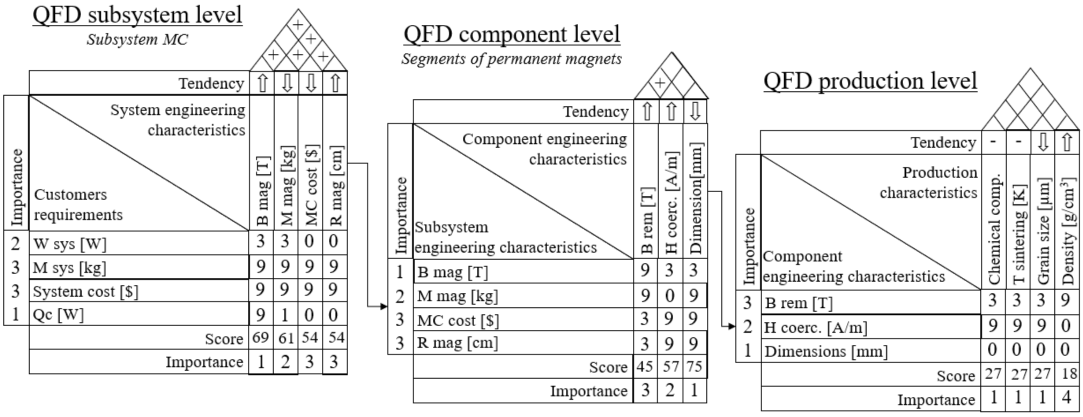


Source: Oliveira *et al*. (2023b)

The most crucial component of AMR is the MCM. The particle diameter (dP) is by far the most critical EC of this component since it is directly related to the superficial area in contact with the fluid flow, its friction factor, and Nusselt number, which all affect the pressure drop and heat transfer. Following the QFD framework, the team extended the deployment to the production level. The chemical composition represents the most critical fabrication parameter to deliver the component value. It is because its composition results in the Curie temperature. Employing a material with a proper Curie temperature will guarantee a maximum MCE (BARCZA *et al*., 2011; FUJIEDA; FUJITA; FUKAMICHI, 2022).

The MC goal is to provide the magnetic field over the MCM to generate the MCE. The critical EC are the magnetic field (Bmag) related to the cooling capacity in the AMR, the magnet mass (Mmag), and the MC cost, which comprises the most significant source of project costs. The second level matrix for the permanent magnets composing the subsystem leads to the conclusion that its dimensions are the parameters that impact most the performance of the MC. Furthermore, analogously to the AMR, the component design presented no trade-offs in the roof of the matrix. The production level deployment demonstrated three fabrication parameters critical to the component, which are the chemical composition, the sintering temperature, and the grain size of the magnet.

Figure 4.6. Simplified deployment for the MC, permanent magnets, and production.

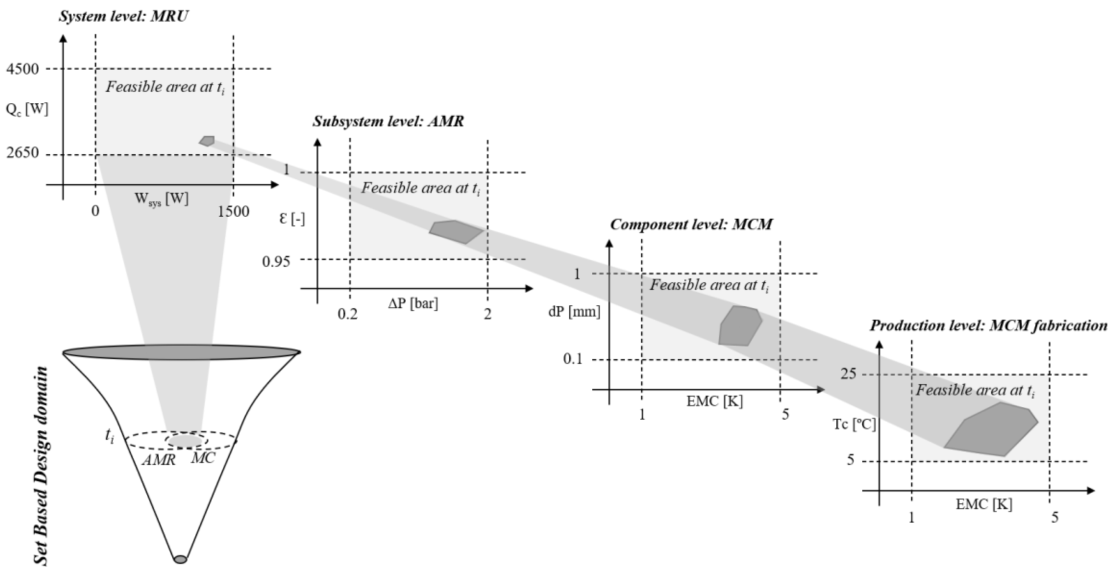


Source: Oliveira *et al*. (2023b).

Cooling capacity and power consumption translate the main requirements for refrigeration systems. They grasp the capacity of cooling the environment whilst consuming power at a competitive level with conventional technologies. By going downward at the subsystem level, the AMR performance is explored via the effectiveness (ε), which characterises the fluid and solid heat transfer, and the pressure drop (ΔP), which represents the hydraulic resistance for the fluid flow. Going downwards even further, at the component level, the MCM is characterised by the particle diameter (dP), which is directly linked with the superficial area of the porous media, and the MCE, which is proportional to the refrigerant effect.

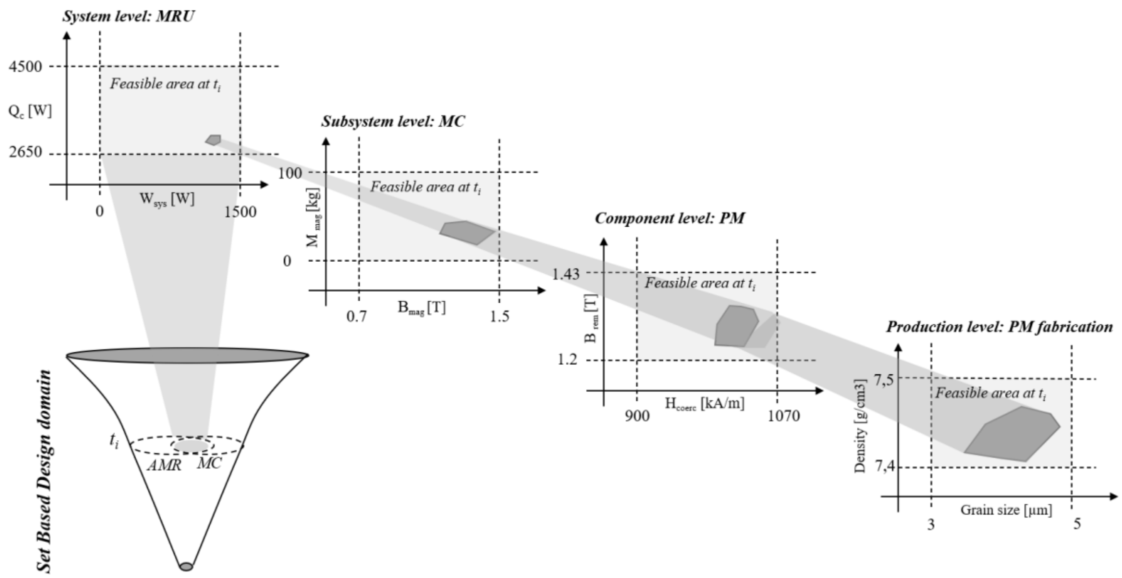
Figures 4.7 and 4.8 present the propagation of the DS. The system dictates that the current power consumption range is from 0 W to 1500 W, and the cooling capacity is between 2650 W and 4500 W. To achieve such goals, the AMR must operate with a pressure drop from 0.2 to 2 bar and effectiveness between 0.95 and 1. Higher pressure drop implies extrapolating 1500 W, and lower values for effectiveness lead to insufficient cooling capacity. The propagation goes on to the MCM level, in which it must have a particle diameter from 0.1 to 1 millimetre to keep pressure loss and effectiveness between the required range values in AMR. Furthermore, the MCE must operate between 1 to 5 K to enable the cooling capacity required by the system. Finally, considering the production of the MCM, the range of the Curie temperature to guarantee the intensity of the MCE is between 5 °C and 45 °C for room temperature applications.

Figure 4.7. Upward and downward DS propagation for the AMR.



Source: Oliveira *et al.* (2023b).

Figure 4.8. Upward and downward DS propagation for the MC.



Source: Oliveira *et al.* (2023b).

TRL-6 prototypes require a competitive design with compatible costs. Given the high costs of magnetic materials, we analysed DS propagation to keep the project under budget, which is most affected by the mass of some components. The MC will manage the cost restriction by the applied Magnetic Field (B mag) and the permanent magnets (M mag) mass. The B mag must be high enough to enable the system to operate according to the cooling capacity but low enough to remain within budget restrictions. Thus, for B mag the DS must be from 0.7 to 1.5 T. Similarly, the mass of permanent magnets must be from 20 to 100 kg. Following the propagation to the component level, the mass of segments of permanent magnets is dictated by coercivity (H coerc) and remanence (B rem). To remain under budget, the H coerc DS is delimited by 900 to 1070 kA/m, and the B rem from 1.2 to 1.43 T. At the production level, what dictates the component performance are its grain size and density, which must be between 3 and 5 µm and 7,4 e 7,5 g/cm, respectively.

The outcomes of the component-production levels are fundamental to evaluating alternatives regarding manufacturing issues. Figures 4.7 and 4.8 demonstrate that manufacturing challenges propagate upward to the system level. Thus, especially in this case, understanding the production and applying its analysis in the system design was crucial for the project's success. For instance, manufacturing limitations restrict the size of the particles of the MCM. Designers must understand these restrictions to input the NDP. They affect the project since higher dP values restrain the maximum effectiveness, which limits the cooling capacity achieved. Based on this, strategies to compensate for this effect are necessary.

Manufacturing parameters such as the sintering temperature of the MMC affect its engineering since they are fundamental for providing its magnetocaloric properties. It can be further exemplified by the problem of shaping the MMC into the AMR component. Most materials are brittle, and their machining/forming is a challenge. It is intensified for the necessity of a specific particle size distribution in packed bed AMRs. TRL-6 products are not designed for high-scale manufacturing. For this reason, the quality level of the QFD was not considered. The value definition and deployment finished by establishing challenges for each part of the product (Table 4.2).

4.3. TRADE-OFF CURVES GENERATION

The QFD provided an overview of the conflicting parameters at the system and subsystem levels (Fig. 4.9). The most crucial trade-offs for the entire project are the ones ruling the system-level decisions. They represent a governing triad formed by the cooling capacity, power consumption, and system cost. The system performance regarding these parameters will define the possibility for the technology to advance to the next level. They characterise a pivotal trade-off since the increase in the cooling capacity demands either an increase in the power consumption or in the cost of the system (PEIXER *et al.*, 2022b). The generation of ToC for the project was planned to prioritise the analysis of these relations (OLIVEIRA *et al.*, 2023a).

Table 4.2. Challenges for subsystems

Subsystem	Challenge
Active Magnetic Regenerator	To design a set of AMR capable of providing the conditions for the system to achieve the necessary cooling capacity and temperature span, aiming to minimise power consumption and mass.
Magnetic Circuit	To design a MC capable of providing the variation on the magnetic field required by the system to achieve the necessary cooling capacity and system temperature span, aiming to minimise the mass.
Hydraulic System	To design a HS that enables a reliable operation, providing the required frequency and mass flow rate, aiming to minimise the power consumption and noise generation.
Heat Exchangers	To design HEx that enables a reliable operation, providing the required effectiveness, aiming to minimise the power consumption and noise generation.
Transmission System	To design a transmission system that enables a reliable operation, providing the required frequency of the system, aiming to minimise power consumption and noise generation.
Control System	To guarantee that the system will operate within the conditions established by the EC, aiming to minimise the power consumption and noise generation.

The presence of many contradictions reflects the intricate character of the project, which demands the precise synchronisation of parts to deliver value. Nevertheless, the extensive demand for trade-off analysis and the few resources available for building prototypes and performing experiments, much influenced by the high cost of materials, led the team to rely on computational tools to enable the SBD of the MRU. Model-based ToC paved the way for directing experiments to validate crucial information. The system impact and availability of data and resources were considered when planning ToC generation.

The equations for modelling the AMR were conservation of mass, momentum, and energy applied in a porous medium composed of spheroidal particles. For the MC, the application of Maxwell Equations for magnetostatics underpinned the model. Geometric and operating conditions enabled the coupling of all subsystems (see OLIVEIRA *et al*., 2023b). Designers focused on reducing the computational cost while maintaining model accuracy. They employed ML models and polynomial features techniques to capture the nonlinear behaviour of the phenomena and a Ridge regression to prevent the overfitting of the data (see LIMA *et al*., 2022). Subsequently, designers performed experiments to validate the agreement of the numerical simulations with experimental results (Fig. 4.10).

Figure 4.9. Simplified overview of trade-offs.

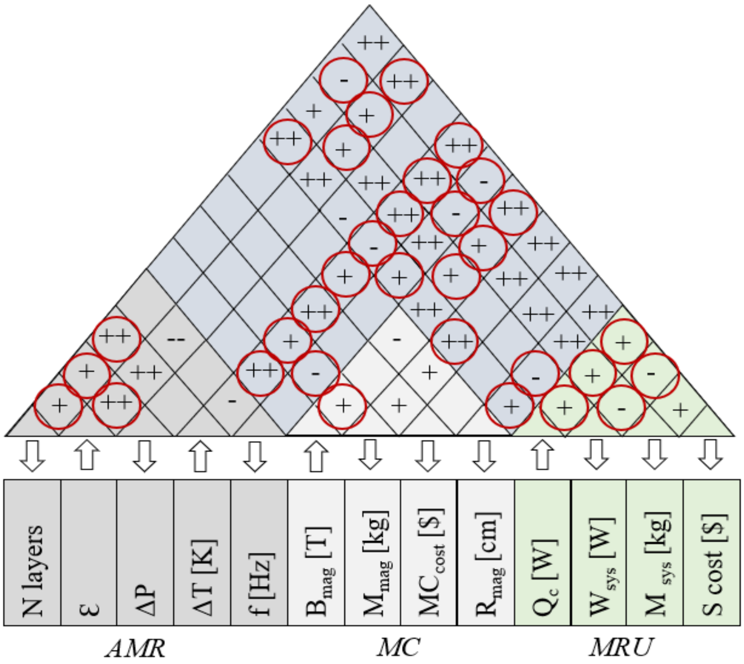
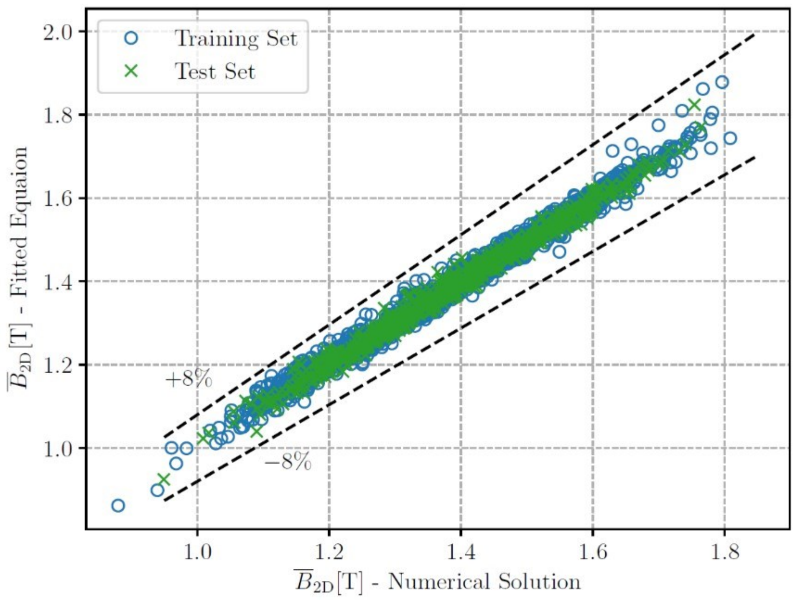


Figure 4.10. Validation of numerical simulations.



Source: Oliveira *et al*. (2023a)

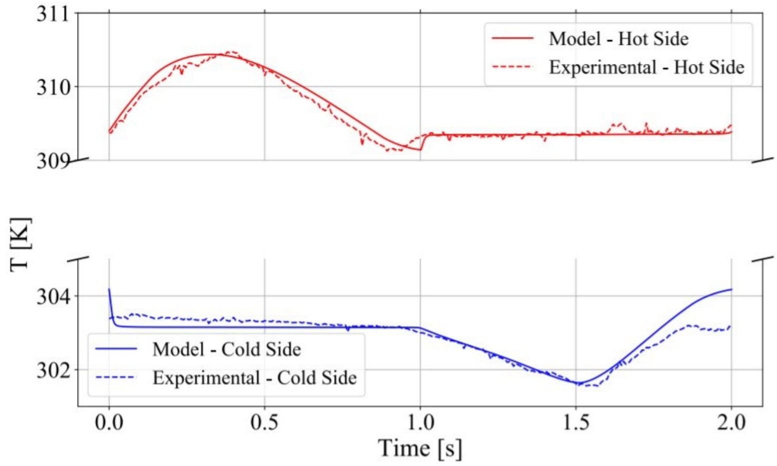
Coupling governing equations established links between the design parameters of each subsystem, as well as the performance metrics of the system. To understand the coupling of equations, two cases are exemplified. The AMR and HEx are connected by the working fluid, which flows through the regenerator beds and HEx according to the AMR cycle. Hence, they are coupled by the energy and mass conservation of the fluid flow through the regenerator and HEx. It implies that the mass flow rate and the fluid flow temperature are the same leaving the AMR during the hot and cold blow and entering the cold and hot HEx, respectively. The second example is the gap between the rotor and stator where the AMR is placed, and the magnetic field is generated.

From the MC perspective, the shorter the distance between the rotor and the stator, the better since it increases the magnetic field applied to the AMR, and the cooling capacity. Nevertheless, considering the AMR, the greater the gap, the better since it enables more space to increase the volume and mass of MCM. Thus, an intersubsystem trade-off directly affects the gap design and its evaluation on a limited level would not be adequate. Thus, the AMR and MC must be mathematically coupled by the geometric restrictions each component imposes on the other. The AMR is placed inside the gap between the rotor and the stator, and the magnetic field provided by the MC is achieved considering the geometric restrictions of the gap (OLIVEIRA *et al.*, 2023a).

Designers determined the objective functions, restrictions, and operating and boundary conditions of the simulations based on the value definition results, which include understanding subsystems limitations and initial DS bounding. Two of the most relevant system-level restrictions are the overall system mass and the maximum frequency, which connected SBD and PBD since it is impacted to the technological limitation of valves composing the HS. Once boundary conditions were set, the team performed experimental tests to validate governing equations, ensuring their reliability. This validation for the AMR was one of the most resource-consuming steps during the project since regenerators are not applied in any other engineering systems, and they have no consolidated modelling procedures.

The team developed mathematical correlations and verified results experimentally in an exhaustive process until they obtained adequate deviations for the design of the systems. The comparison between the mathematical models developed for the AMR and the experiments is presented in Figure 4.11 (see VIEIRA *et al.*, 2021). Model-based ToC were generated only after the validation of models. In order to get an overview of the impact of the governing triad on the system at all levels, three parameters emerge as critical for ToC: the cooling capacity of the system, the mass of magnetocaloric material, the outer radius of the MC, and the mass flow rate.

Figure 4.11. Model vs. experiments.



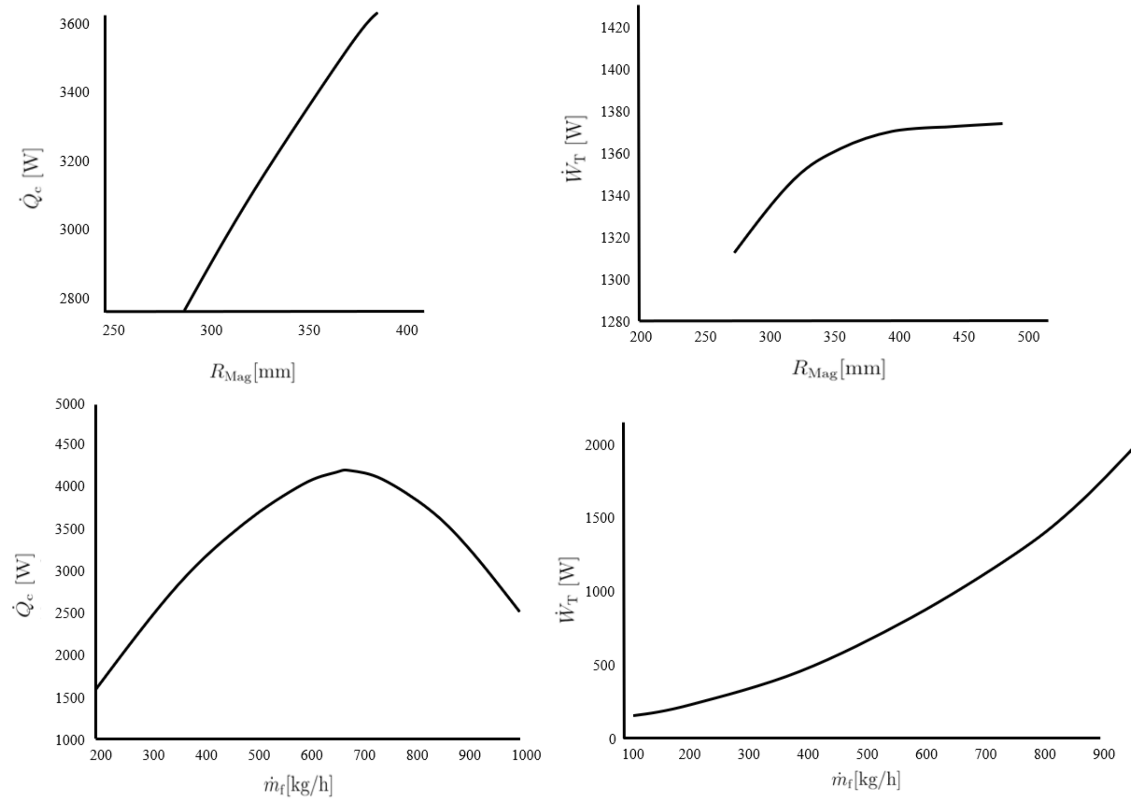
Source: Oliveira *et al*. (2023a)

Figure 4.12 presents some model-based ToC generated to grasp the governing triad, exemplifying the case. The cooling capacity (Qc) and the outer radius of the MC (Rmag) are directly proportional. When Rmag is higher, Qc increases. Nevertheless, this is not the desired behaviour for these parameters to assume in the project. It is necessary a higher Qc since it determines the capacity of the system to generate cold, and also a lower Rmag since it diminishes costs. The same goes for the mass flow rate and power consumption. A higher mass flow rate increases the cooling capacity but leads to a rise in system losses leading to higher energy consumption.

4.4. DEFINING THE LEVEL OF INNOVATION FOR SUBSYSTEMS

The challenges pertaining to MRU development made it crucial to use resources strategically for designing and achieving development goals. They include the scarcity of knowledge and lack of previous experience from industry and academia, high costs of rare-earth elements and MCM, and reduced teams due to specialisation requirements and budget. The scarcity of resources offers a scenario in which adopting SBD is quite complicated due to its resource-consuming nature.

Figure 4.12. Model-based trade-off curves.



Source: Adapted from Oliveira *et al*. (2023a)

Adopting SBD means defining the LI and developing subsystems with low innovation requirements according to the PBD precepts. TRL-6 products do not present a consolidated knowledge background, which compromises the ability of engineers to evaluate the DS screening regions to discard or focus. Thus, in this case, the LI provided a path to balance resources for the NDP. Table 4.3 presents an overview of product levels and their impact on the system.

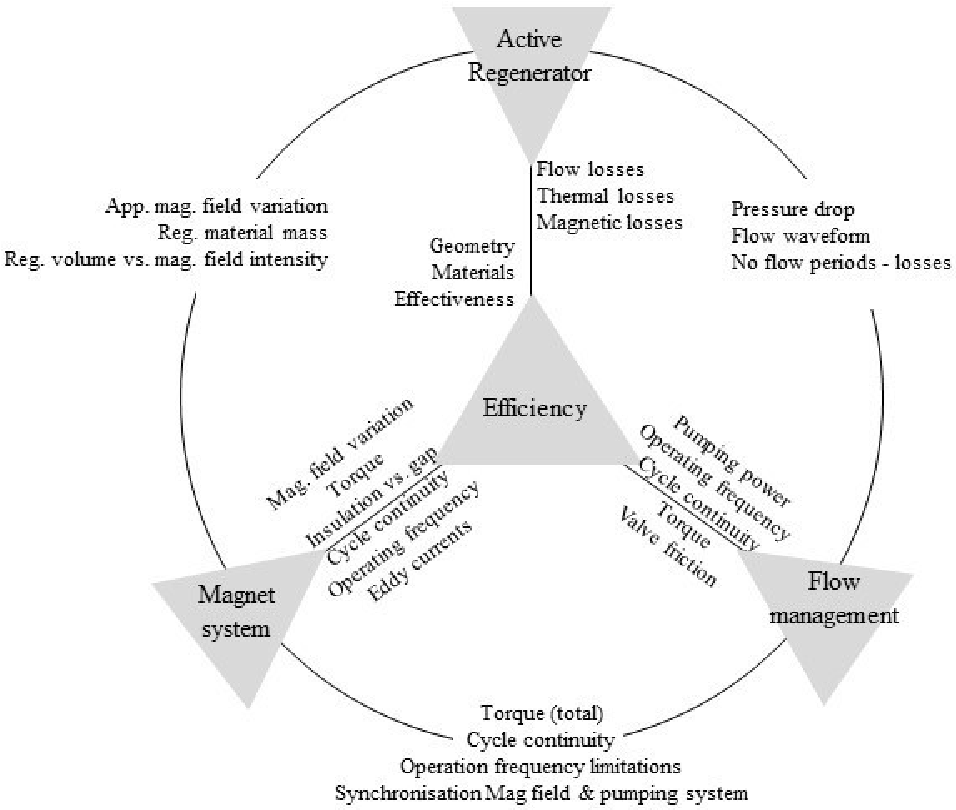
Value definition inputted the LI definition by outlining requirements, parameters, and variables of interest. Furthermore, it fostered the investigation of constraints, system impact, and interrelations among subsystems (Fig. 4.13). The AMR severely impacts the system since most of the overall power consumption is subject to its design. It influences other subsystems by dictating the heat transfer in the thermal reservoirs and the requirements of hydraulic and magnetic parameters of HEx, HS, and MC (OLIVEIRA *et al.*, 2022b). The MCM composing the AMR has low TRL, few suppliers worldwide, and no similar applications in industry or academia.

Table 4.3. Overview of the subsystems of the product and interactions

	Function	Parameters	Availability & Tech. Dev.	Impact on	
				system	subsystem
HS	Fluid flow management	- Frequency - Mass flow rate -Power consumption	High	-Power consumption	- AMR and Hex frequency - Mass flow rate
HEx	Thermal interaction (AMR and thermal reservoirs)	- Effectiveness - Mass flow rate -Power consumption	High	-Power consumption - Volume - Heat transfer on reservoirs	- AMR inlet temperatures
AMR	Generation of the refrigerating effect	- Mass of MCM - Mass flow rate - Power consumption - Frequency - Magnetic field	Low	-Power consumption - Heat transfer on the reservoirs -Cost of the system	- HEx and MC heat transfer and magnetic requirements
MC	Generation of the magnetic field	- Magnetic field - Magnetised volume - Mass of permanent magnets	Low	- Cost of the system - Volume	- AMR magnetic field and magnetised volume

Source: Adapted from Oliveira *et al.* (2022b)

Figure 4.13. Correlations between the components and design parameters of an MRU.



Source: Adapted from Barbosa Jr., Lozano, and Trevizoli (2014).

The MC is responsible for the largest share of the overall cost and volume, and it is deeply interconnected with the AMR, determining the applied magnetic field and allowing magnetised volume for allocating the MCM. Even though MC is a mature technology employed in several industrial applications, the technological development for MR is insipient with low market availability. Similarly, the HEx has a considerable share of the overall power consumption and volume. It dictates, along with the AMRs, the heat transfer rates in the thermal reservoirs. Nevertheless, even though the application of HEx in MR is also insipient, several engineering applications adopt similar models, including refrigeration and heat-pumping systems.

The HS influences power consumption to a minor degree compared to the AMR and HEx. It affects other subsystems by dictating mass flow rate and frequency. The parts composing the HS are extensively applied in several technologies with an extended operational range, including valves and pumps with several options in the market, for example. The control and transmission systems follow the same scenario. Their design does not represent a critical influence in the system since they are consolidated technologies operating in a wide range of points and applications. They represent CHTF solutions selected and coupled in the system at the end of the NDP. Their design is not approached in this Doctoral Dissertation since they are not critical to demonstrate the hybrid development approach and due to Dissertation length issues. Table 4.4 presents the LI matrix for the MRU.

Table 4.4. Innovation matrix of the magnetocaloric refrigerator

	HS	HEx	AMR	MC	TS	Control
Market availability	++	++	--	--	++	++
Technological development	++	++	--	--	++	++
Impact on the system	-	+	++	++	-	-
Impact on subsystems	+	+	++	++	-	-
Innovation level	low	medium	high	high	no	no
Development strategy	**CHTF**	**CUTF**	**SBD**	**SBD**	**CHTF**	**CHTF**

Source: Oliveira *et al.* (2022b)

The AMR and MC have not consolidated technologies for application in MR systems. They followed an SBD strategy since their low maturity and high impact represent a considerable risk for the project. The HS and HEx, on the contrary, present a wide technological availability and are suitable for a PBD strategy. Consequently, the HS is a CHTF since it is a widespread technology with commercial solutions, medium impact on other subsystems, and little influence on the system performance. Its commercial availability reduces the development risk of the component.

In contrast, HEx represents an established technology with several options in the market. However, it impacts the overall system performance and influences other subsystems to a certain degree (PEIXER *et al.*, 2022a). Therefore, it requires technological customisation since selecting a solution to attend to the restrictions demanded by other subsystems might diminish system performance. Thus, designers considered customisation in a CUTF approach to fit the product.

4.5. PLANNING AND MANAGING THE LEAN PRODUCT DEVELOPMENT OF THE MRU

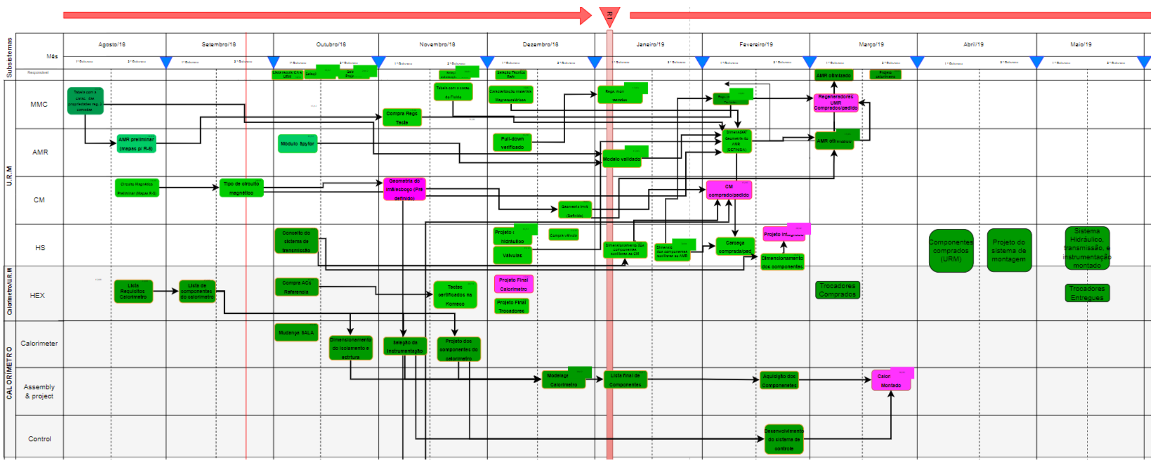
The definition of value and challenges for each subsystem, the LI intended for each part of the product, and the sponsors' requirements underpinned the planning. Given the TRL-6 project and the collaboration environment, the leadership and the customers defined semi-annual milestones characterised by reports containing information regarding experiments and analysis results, computational model deliveries, decision-making, and knowledge acquired about the technology and the product. These reports served as pacemakers, establishing macro deliveries for each part of the product to gather information and the necessary knowledge to generate the report. Table 4.5 presents four reports and their main requested deliverables.

Considering the first report, sponsors and leadership expected that DS investigation in the first six months would provide a clear perspective of the operating point and dimensions of the MRU at the end of the project. Furthermore, designers expected results from property characterisation tests and mathematical models to support decision-making regarding experimentation and resource balancing. These deliverables were allocated over the first six months and deployed into smaller deliverable packages assigned to each subsystem. Figure 4.14 presents a miniaturisation of the DR of subsystems for the first ten months of the project.

Table 4.5. Report to sponsors and the main deliveries

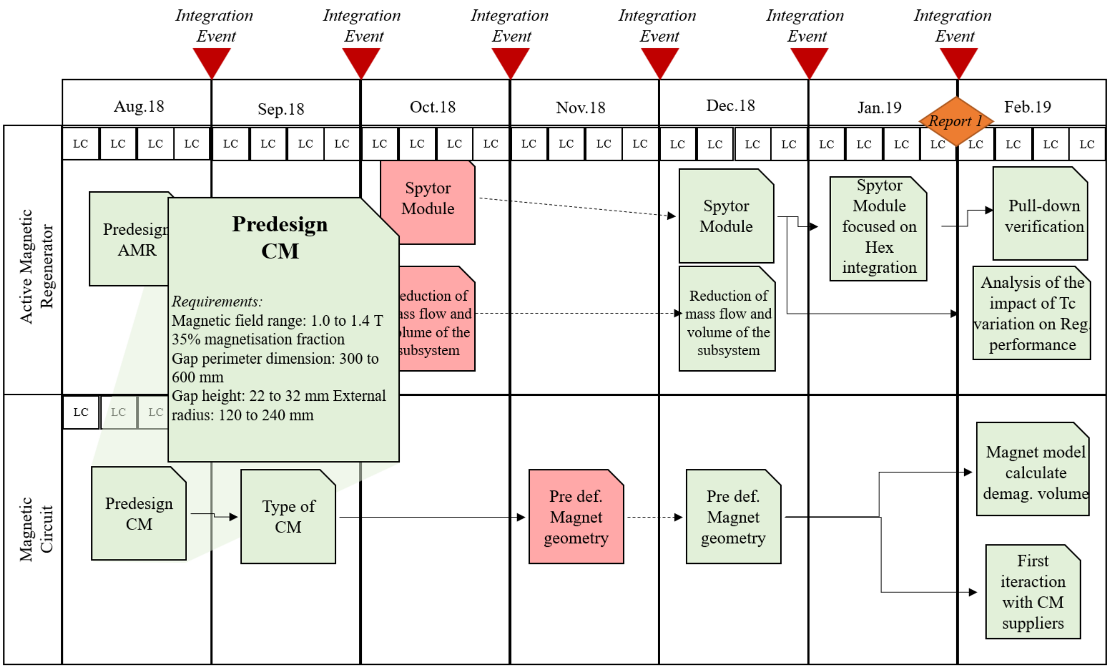
Report	Delivered by	Content
Report 1	After six months	(1) MRU first range definitions: operation point and size;
		(2) Definition of bounding conditions for the design of subsystems;
		(3) Mathematical model for subsystems and integration;
		(4) Schematic design of the MC;
		(5) Characterisation of magnetic properties of materials;
		(6) Study of a reference air conditioner.
Report 2	After twelve months	(1) Mechanical and acquisition project of the MC;
		(2) Mechanical project of AMR multilayer;
		(3) Integration and optimisation of HEx to fit the system;
		(4) Preliminar assembly of MRU.
Report 3	After eighteen months	(1) Integration prototype assembled and tested in a calorimeter;
		(2) Certified tests of MRU;
		(3) Miniaturisation of the MRU;
		(4) Experimental mapping to define final parameters.
Report 4	After twenty-four months	(1) Magnetic air conditioner prototype tested in calorimeter;
		(2) Optimisation of final parameters for air conditioner.

Figure 4.14. Deliverable Roadmap for the MRU.



To demonstrate the planning for the project, Figure 4.15 presents a simplification of the DR and some deliveries accomplished in the project. Horizontal lanes represent MRU subsystems, and vertical lanes represent months. The team planned IE and LC to deliver the report at the end of every six months. Weekly TKDev meetings happened for each subsystem. As shown in Figure 4.15, the value definition inputted the DR by delineating requirements for achieving the delivery goals. The connection between value definition and design activities begins by integrating QFD results with the deliveries.

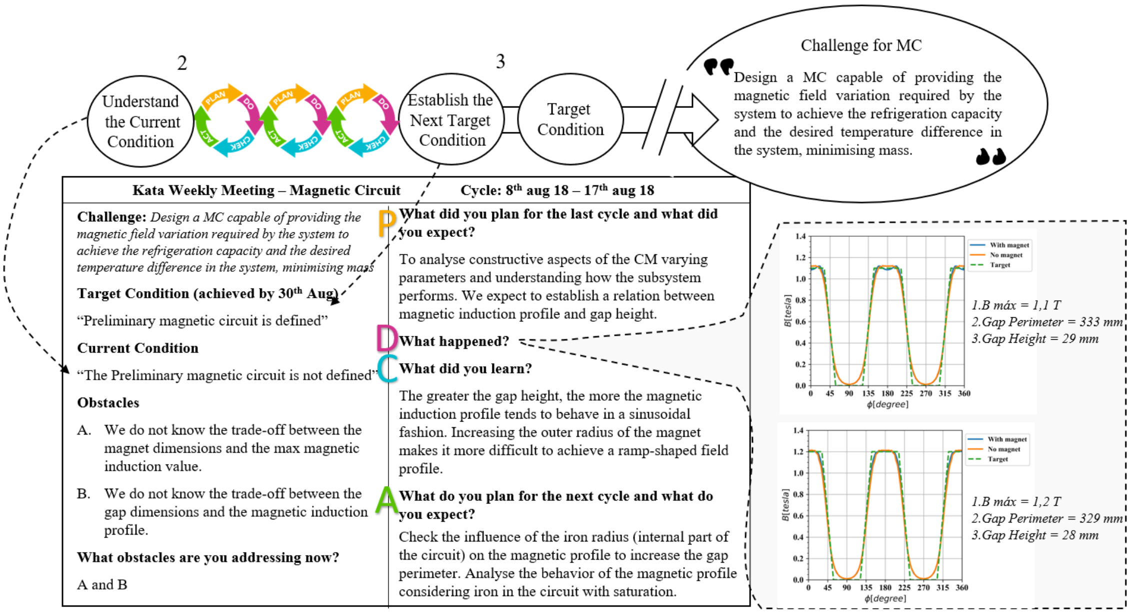
Figure 4.15. Simplified Deliverable Roadmap for SBD subsystems.



According to Table 4.5, the first report requires a schematic design for the MC. Thus, this delivery is deployed into the preliminary design of the CM, the definition of the type of CM, and its geometry, through experimentation and elimination of alternatives. This rationale guided the deployment of several deliveries that were distributed over time. The team conducted short LC to achieve them, based on the TKDev. Figure 4.16 shows a simplified example of a real storyboard from the MC. Since delivery was set for the preliminary design of the CM, it became a TC for the subsystem. In the real storyboard, this condition is described in detail with the aimed status of knowledge necessary to acquire to perform the preliminary design. The CC is described concerning the TC detailing the current knowledge status.

The moment captured in the storyboard shows that the MC identified two obstacles preventing achieving the TC, which were the necessity of studying trade-offs between MC parameters to narrow values for the design. Thus, they analysed constructive aspects, generating the ToC and varying parameters and understanding their impact on the subsystem. The team presented the results during the CK session. In the example, they varied the magnetic field, the gap perimeter, and the gap height to study the behaviour of the magnetic profile. These experiments led the team to learn two important patterns: “the greater the gap height, the more the magnetic induction profile tends to behave in a sinusoidal fashion" and "Increasing the outer radius of the magnet makes it more difficult to achieve a ramp-shaped field profile".

Figure 4.16. TKDev learning cycle storyboard.

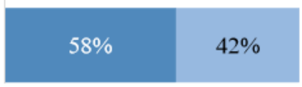


The learning is shared with other subsystems along with the curves in the IE, promoting an environment of knowledge sharing and discussion, focusing on understanding the implications on the system. The requirements from the QFD acted as a restriction for experiments as presented in the storyboard (Fig. 4.15). The team tested values inside the ones established, staying within sets once committed. In the example, MC studied the effects of varying the magnetic field in 1,1T and 1,2T. Nevertheless, in the real storyboard, all values from 1,0T to 1,4T were tested. It demonstrated how the QFD inputs the NDP and the planning of LC and IE. It will provide requirements and restrict experimentation at all levels of the product.

The CE and the integration engineer conducted the CK with all subsystems. Given the simplicity of the organisational structure, the TK cycles were conducted just at one level, i.e., it was not necessary to further deploy to subsystems teams. Each CK for each subsystem lasted approximately 30 minutes with a weekly frequency. First, only SBD subsystems integrated the CK session. Later in the project, PBD parts of the product also adhered. The Doctoral Researcher observed sessions and iterated with teams to assure TKDev was being properly followed, and the storyboards were correctly filled.

Teams executed 65 LC and 238 CK sessions, which totalises more than 100 hours. Table 4.6 presents managerial metrics collected during development. The results show a general improvement comparing the first year with the second. A possible reason for that is knowledge gaining, i.e., more knowledge about the project implies better planning. At first, the expectation was to overcome obstacles and reach the TC with a certain number of actions. However, several times the teams had to replan actions or take unexpected countermeasures due to unexpected outcomes or problems along the way.

Table 4.6. Main performance Indicators originated in TK sessions

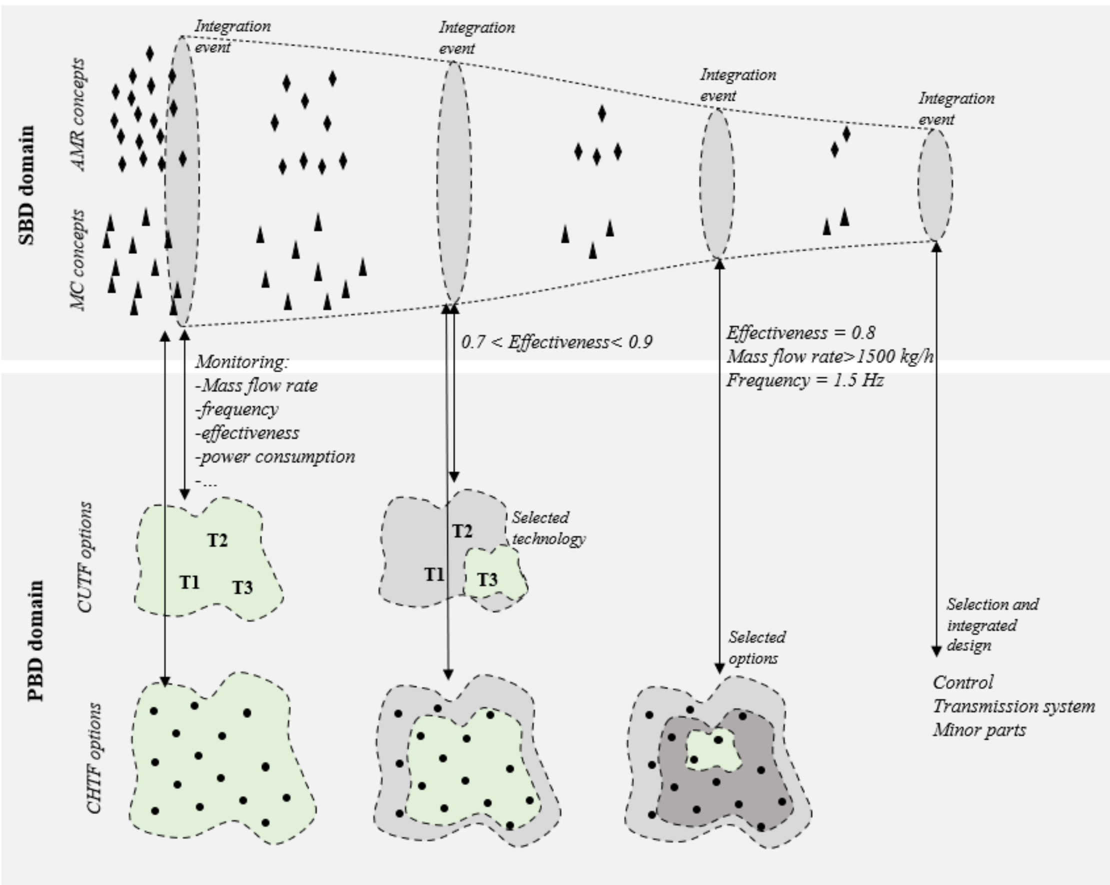
Indicator	Year 1	Year 2
Planned vs. Unplanned actions. *Planned actions* *Unplanned actions* **Measure how much of the actions taken in each cycle was planned in the previous cycle.**		
Planning assertively *Concluded* *Non concluded* **Measure how much of what we plan for the cycle is concluded on the cycle.**		
Mean overdue time for TCs **Measure the mean overdue time to reach TCs in the project**	61 days	28 days
Mean time between coaching cycles **Measure how frequent the Coaching Sessions were performed in the period.**	10 days	7 days
Mean number of cycles to overcome obstacles **Measure how many LC are necessary to overcome the obstacles of the project**	3,03	3,05

An example is the errors and unexpected behaviour of simulations, demanding additional time to investigate and correct the problem. It caused delays in the project. Nevertheless, the planning precision improved significantly as the team undertook countermeasures and understood the time necessary to perform certain tasks. Another factor contributing to the improving managerial results was the regularity and increased frequency of coaching sessions. Furthermore, during the second year of the project, PBD subsystems and the integrated project began to participate in the LC and IE, contributing to better results. These designers also had experience with the TKDev from previous projects (see OLIVEIRA, 2017).

4.6. THE NARROWING-DOWN PROCESS AND THE HYBRID DEVELOPMENT APPROACH

Adopting a hybrid development process was necessary to enable focusing on the AMR and MC DS exploration to learn about the duality of the subsystems and match the resources available. It would be unfeasible to carry out all subsystems under the SBD umbrella. Thus, the most critical subsystems were developed based on the SBD, and the subsystems with greater certainty of finding a solution compatible with the product were chosen using a PBD approach. Figure 4.17 shows the connection between domains focusing on the most critical parameters connecting the PBD and SBD subsystems.

Figure 4.17. Hybrid development approach for the MRU.

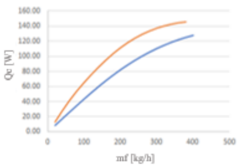


Most parameters first bounding originated in CR and competitor products, considering the TRL-6 goal of operating and achieving at least a similar conventional technology performance. Furthermore, results from simulations to understand range values that would offer the required performance were also performed simultaneously with the ToC generation. Following the four main parameters representing the governing triad of the system, the NDP will be presented for the cooling capacity of the system, the power consumption, the outer radius of the MC, and the mass flow rate.

The initial DS for the cooling capacity was set to be superior to 2.9 kW and the power consumption to be inferior to 1.5 kW, in order to be competitive compared to other products and to prevent a drop in efficiency. The delimitation of these two system parameters guided the NDP at subsystem levels. The first bounding of the mass flow rate came from knowledge obtained through LC (value higher than 360kg/h), as presented in the simplified storyboard in Figure 4.18.

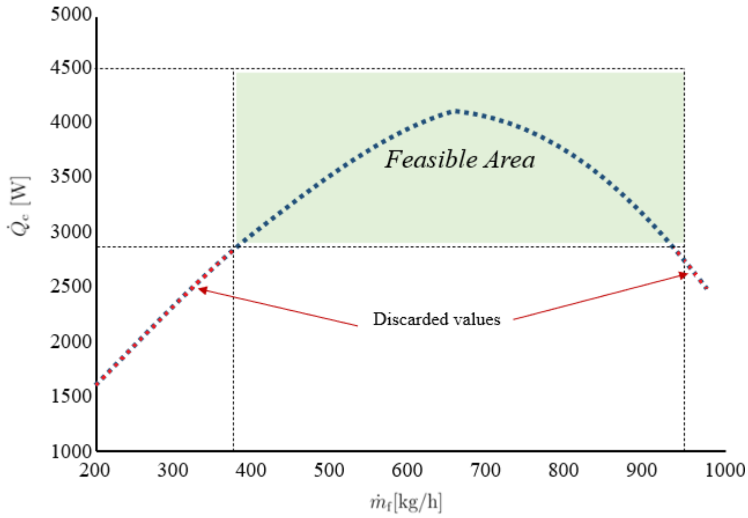
Figure 4.18. Storyboard learning for design space bounding.

Kata Weekly Meeting – Active Magnetic Regenerator	**Cycle: 23th aug 18 – 30th aug 18**
Challenge: *To design a set of AMR capable of providing the conditions for the system to achieve the necessary cooling capacity and temperature span, aiming to minimise power consumption and mass.* **Target Condition (achieved by 31st Aug)** “The experimental results agree with the model results. We have a predesign of the AMR with 30K span.” **Current Condition** “The experimental results agree with the model results. We have a predesign of the AMR with 250W per regenerator” **Obstacles** A. We did not achieve the required capacity **What obstacles are you addressing now?** A	**What did you plan for the last cycle and what did you expect?** To simulate different regenerator sizes to analyse the behaviour of the cooling capacity. We expect to get 4kW. **What happened?** We tested different regenerator lengths. **What did you learn?** We can obtain the required cooling capacity only with a minimal mass flow rate of 360 kg/k and 150mm length. **What do you plan for the next cycle and what do you expect?** Analyse the possibility of increase the number of layers and understand strategies for optimise Curie temperatures and analyse the impact in the cooling capacity



Following LC, experimentation, and simulation enable to understand that subsystems together would only reach the desired cooling capacity for a mass flow rate higher than 380 kg/h. Subsequently, generating the model-based ToC, designers learned that for values of mass flow rate surpassing 950 kg/h, a drop in cooling capacity for values below 2900W is observed (see Fig. 4.19). Since this extrapolates the DS, these system configurations were discarded during the NDP. Thus, the current DS was updated for the mass flow rate between 380 kg/h and 950 kg/h and the cooling capacity for values higher than 2900 W.

Figure 4.19. Narrowing the design space for mass flow rate based on model-based trade-off curve.

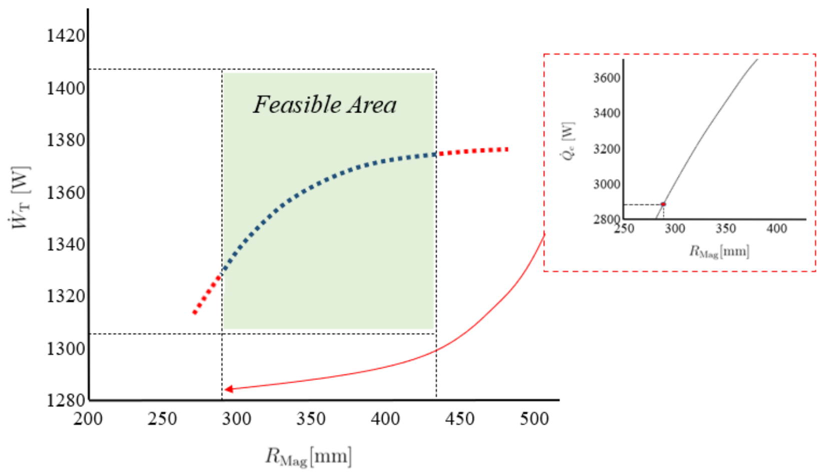


Source: Oliveira *et al.* (2022b)

For the system to have a limitation in the mass of magnets and size, the maximal outer radius was established as 430mm. Experiments and ToC showed that for the value of magnet outer radius below 298 mm, the minimum required value for cooling capacity of 2.9 kW is not obtained. Thus, DS was further narrowed for a magnet circuit radius between 298 mm and 430 mm (Fig. 4.20). Continuing with experimentation and learning, designers discovered that for values of mass flow rate higher than 830 kg/h, the power consumption is superior to 1.5 kW. Thus, the current DS was updated for values between 380 and 830 kg/h (Fig. 4.21).

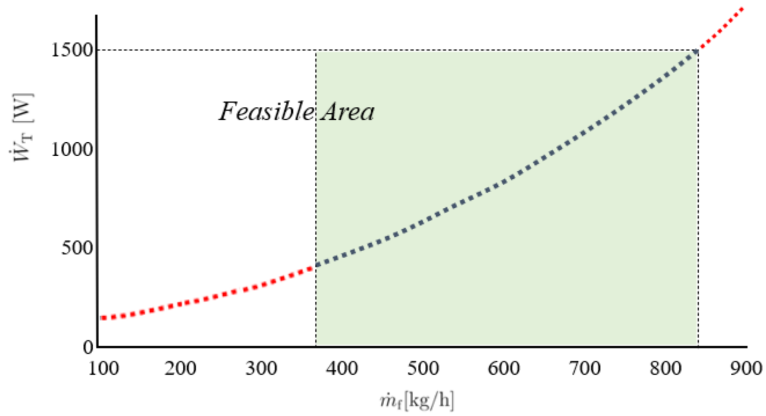
Parameters from different subsystems are usually related to each other through system parameters. Thus, the DS intersection was made based on system referencing, i.e., a subsystem updates the system DS propagating the status to other subsystems. Designers identified through simulation limitations that impact certain design aspects along the various levels of the product. Figure 4.22 presents the 3D model-based ToC connecting contradictions from subsystems and the cooling capacity of the system.

Figure 4.20. Narrowing the design space for magnet outer radius based on model-based trade-off curve.



Source: Oliveira *et al.* (2022b)

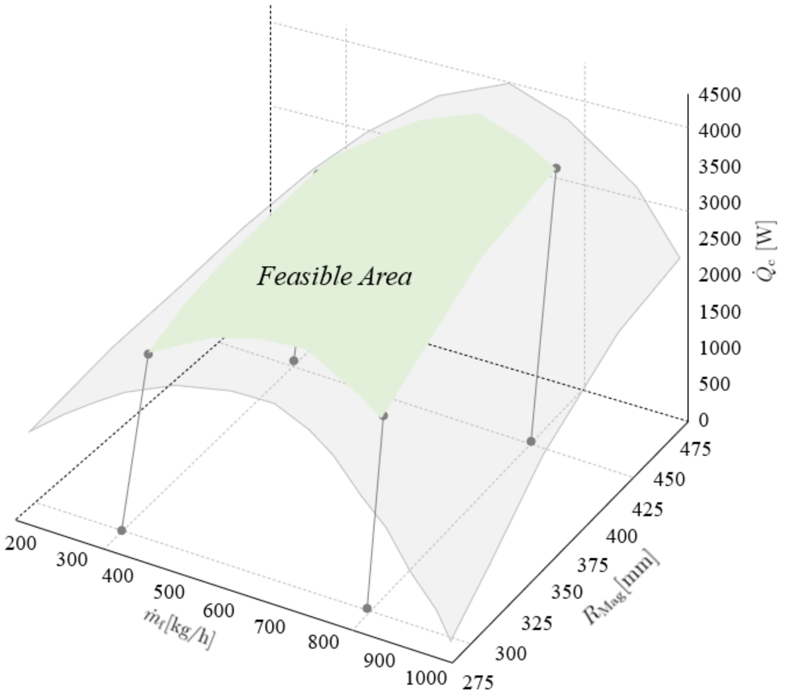
Figure 4.21. Narrowing the design space for mass flow rate based on model-based trade-off curve.



Source: Oliveira *et al.* (2022b)

IE enabled monitoring of the compatibility between the SBD and the PBD domain and provided information for deciding on the start of customisation and choosing options to integrate CHTF solutions. At each integration event, the DS was compared regarding the parameters connecting both domains. Four months after the beginning of the NDP, the project of the HEx began (CUTF), including the subsystem in the TKDev cycles. First, the HEx leader sought to model the coupling of the HEx in the system then he started to test the possible technologies and operation points and understand their impact on the technology.

Figure 4.22. 3D model-based ToC connecting subsystems parameters with cooling capacity

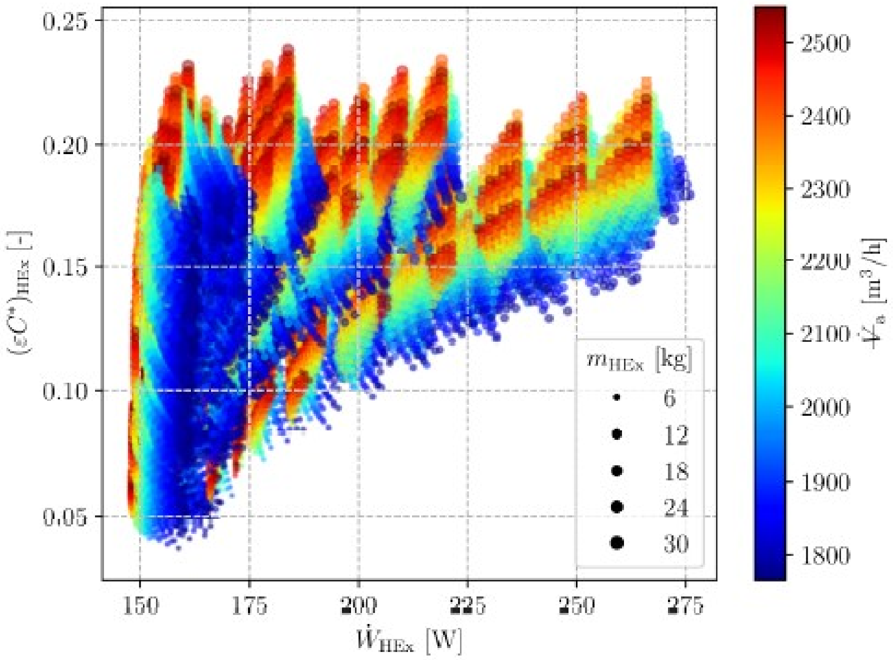


Source: Oliveira *et al.* (2022b)

The leader visited suppliers with consolidated knowledge of air conditioning and HEx to understand restrictions and identify the supplier for the MRU. The main parameters connecting CUTF and SBD domains were the power consumption and the effectiveness required by the system. Designers verified the compatibility of technologies for HEx to attend to the system (Fig. 4.23). Designers compared the project requirements to each option's extent and limitation. Simplified analytical models with fast implementation and low computational cost provided the technological range (OLIVEIRA *et al.*, 2022b).

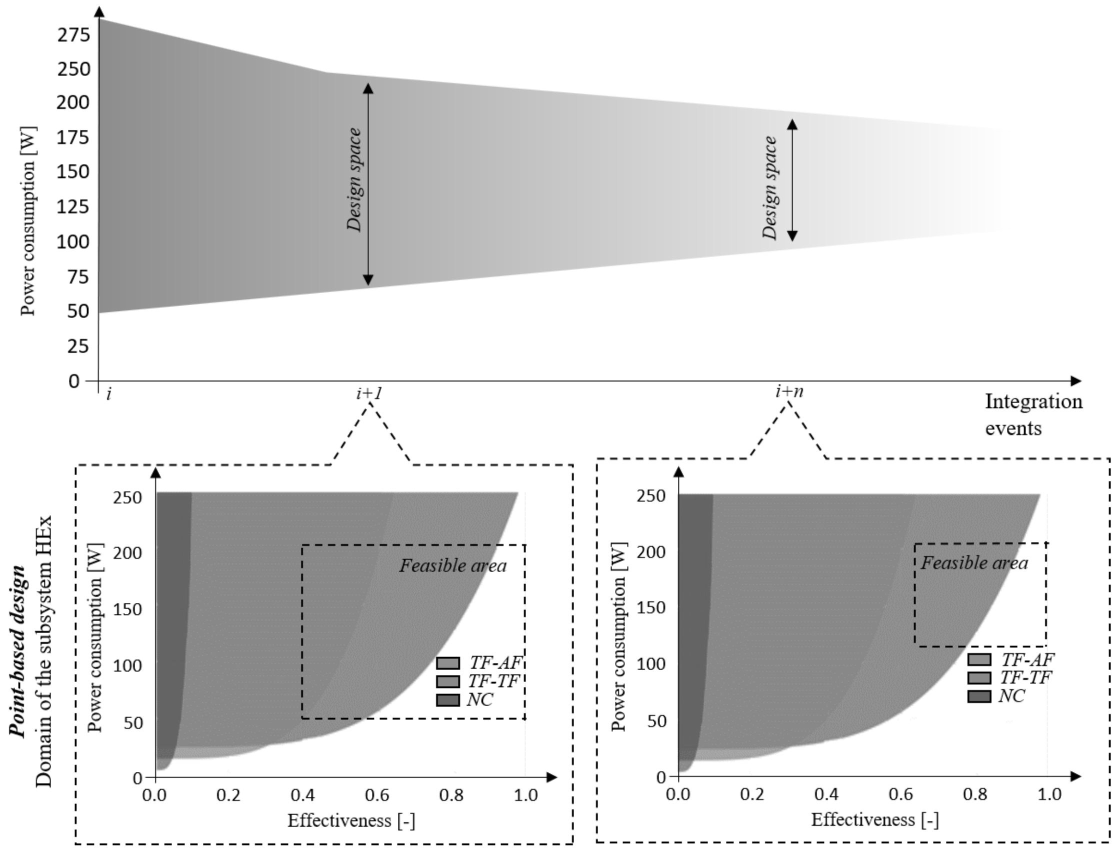
To better demonstrate the monitoring between domains, Figure 4.24 represents the monitoring of the DS and technologies for the influencing parameters of power consumption and effectiveness (Table 4.3). At instant i+1, TF-AF and TF-TF presented an intersection with the feasible design regions. Nevertheless, at an instant i+n, only TF-AF was a viable solution. Designers coupled the AMR and MC with the technology to determine the final design of the component, obtaining customisation guidelines (PEIXER *et al.,* 2022a). Once the technology was selected, several configurations for TF-AF were simulated to customise the project.

Figure 4.23. Simulating and testing HEx configurations



Source: Peixer (2020)

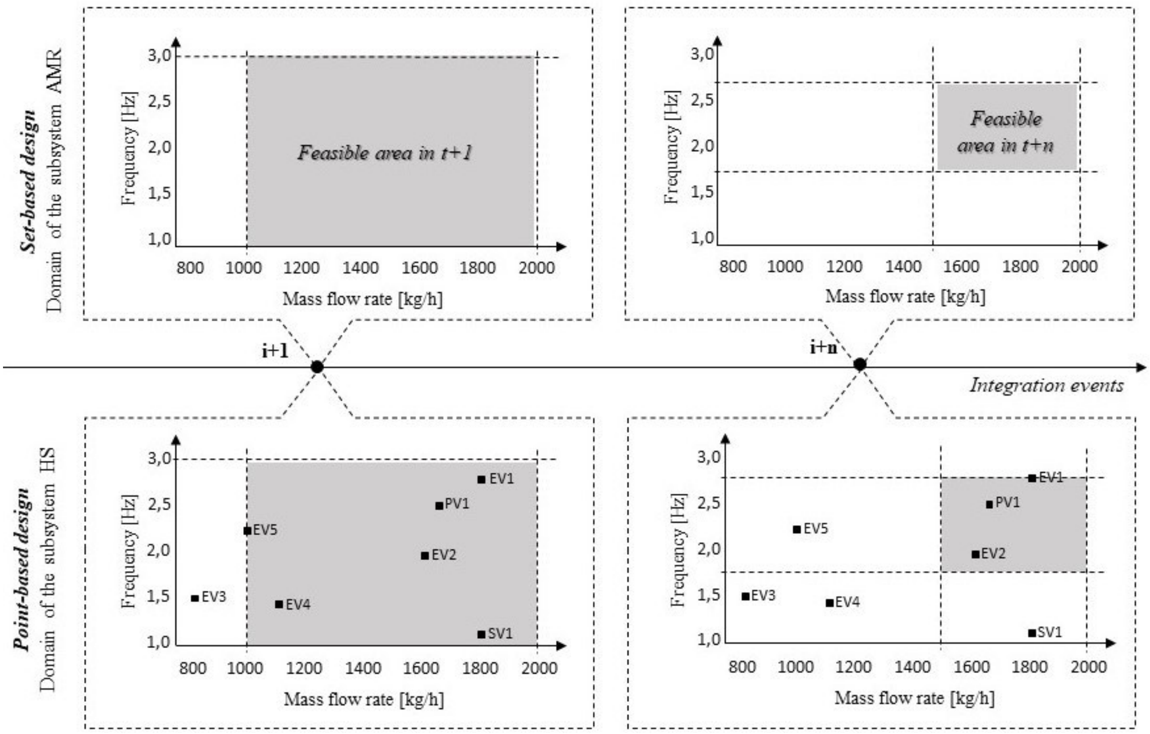
Figure 4.24. Monitoring design space for CUTF. Tube Fin with Axial Fan (TF - AF), Tube Fin with Tangential Fan (TF – TF), Natural Convection (NC).



Source: Oliveira *et al*. (2022b)

The main parameters influencing the choices for CHTF solutions were the frequency and the mass flow rate. They delimit the feasibility area for the HS and its valves, which are the most critical components. Developers compared several valves to the DS of frequency and mass flow rate to verify the existence of options to attend to system requirements (Fig. 4.25). At instant i+1, several valve alternatives provided conditions to operate the system, i.e., were inside the feasible area. It indicates that the NDP of the AMR and MC (under the SBD strategy) and HEx (under the CUTF strategy) can be carried out independently from the HS.

Figure 4.25. Monitoring design space for CHTF. Electro Valve (EV), Poppet Valve (PV), Spool Valve (SV)[1].

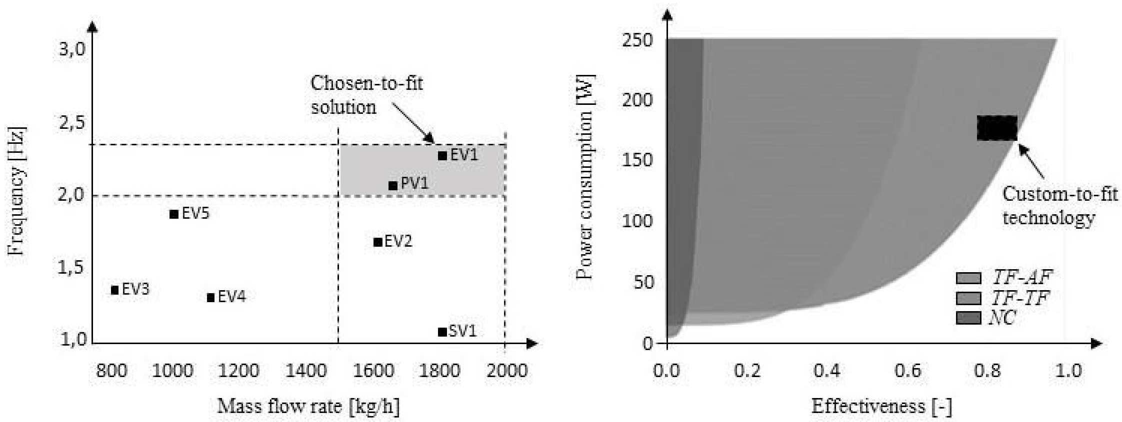


Source: Oliveira *et al*. (2022b)

At instant i+n, the development of the other subsystems enabled the narrowing of the feasible area. Thus, only EV1 and PV1 operate under the restrictions demanded by the system, i.e., a mass flow rate of at least 1500 kg/h and a frequency of 1.5 Hz, as required by other subsystems (PEIXER *et al.,* 2022c). Hence, designers selected EV1 since it presents higher flow flexibility and reliability (SANTOS *et al.*, 2021a; SANTOS *et al.*, 2021b). Given the nature of the solution, coupling the component in the system required a few adjustments for operating under the expected behaviour (PEIXER *et al.*, 2022a). Figure 4.26 presents the results of the CHTF solution and the CUTF solution. After the customisation of the TF-AF, designers coupled the PBD solutions to the rotor-stator arrangement to provide the required performance.

The performance results of the MRU after the process demonstrated that the prototype reached the most significant operating point ever obtained, with a cooling capacity of 490 W at an AMR temperature span of 16.8 ◦C (see PEIXER *et al.*, 2023). Furthermore, this operating condition was sustained in a relevant environment as expected for a TRL-6 level project. Designers further tested the prototype to understand a full-real operating system varying the operation point and analysing performance of key requirements. These results will input the improvement of the MRU and pave the way for the design of the air conditioner.

Figure 4.26. CHTF and CUTF solutions selected for the project.



Source: Oliveira *et al*. (2022b)

CHAPTER 5

RESULTS AND DISCUSSION

This Chapter discusses this Doctoral Research considering the literature gaps and compares the results obtained with the objectives and their potential to advance toward successful implementation cases in more products and organisations. The outcomes of this research reinforce its potential to be the first step toward a referential managerial model and process for SBD. The Chapter is organised into three sections. Section 5.1 provides an extended discussion, analysing the contribution of the Doctoral Dissertation regarding the literature gaps identified in Chapter 2. Section 5.2 presents the results of the application case, focusing on value deployment, model-based ToC, hybrid development strategy, and the impacts of the TKDev on improving the PDP. Finally, section 5.3 provides social, economic, and managerial implications.

5.1. RESEARCH GOALS AND THE OPPORTUNITIES FOR ADVANCING KNOWLEDGE IN SET-BASED DESIGN

The research problem pertaining to this Doctoral Dissertation is the hindering factors acting against SBD implementation, discouraging designers to adopt the strategy. The SBD superiority over traditional product development approaches is acknowledged in the literature. Nevertheless, the fact that it is the most complex and paradigm-breaker element of LPD is not favoured by the absence of general, integrated, and broad guidelines for a development process. This research represents a pioneering effort to gather and consolidate knowledge, connecting the state-of-the-art contributions toward a comprehensive managerial model and process, especially addressing the NDP flow.

The SBR outcomes demonstrated a scenario with several publications regarding SBD in a limited scope, focusing on early stages and introducing tools to find, select, and represent the DS to front-load the NDP. Even though some models aim to present the main steps of SBD, they do it superficially, not detailing crucial aspects that enable the operationalisation of the strategy, such as the management of short LC, IE, and planning. Many efforts were made to develop quantitative, computational, and engineering design-oriented models. It represents relevant advances in important parts of the strategy. Nevertheless, consistent, and well-established guidelines are only obtained through managerial models that can connect and orient the implementation process.

Value definition and deployment is at the centre of any lean implementation, regardless of processes or scope. Value represents the most crucial role in product development. It gained attention in the literature by exploring value definition. Nevertheless, SBD means to effectively deploy value to all product levels to enable the NDP. QFD is a tool with its roots in lean but was not found any application case of its matrices to LPD, except in the master's Thesis preceding this Dissertation.

Value and the QFD are inputs to guide the NDP. Without a robust framework for defining, deploying, understanding, and aligning teams toward value, SBD cannot even begin. One of the most relevant advances in value deployment is the work defining value propagation by Rosen (2015). This multilevel representation implies integrating manufacturing levels in the NDP. It has the potential to shorten time-to-market by starting and advancing the industrialisation process during the product design.

One of the most explored subjects in SBD are ToC. They represent the main tools supporting the NDP and are used to evaluate concepts concerning feasibility areas. Not only SBD but ToC also support PBD in identifying optimal solutions. Even though they can be widely employed and considering the key role they represent in SBD, authors focus on ToC application instead of their contribution to IE and LC. They also fail to recognise their potential to assist designers in balancing resources. The balancing problem can be defined by the gap between the knowledge background designers have to reduce DS, what they need to learn, and the resources available to fill this gap.

With time, the tests, experiments, and ToC form a knowledge background that feeds the development process and enables to save efforts to focus on further exploring options and testing new solutions. When an organisation starts SBD, it will most likely not have the previous knowledge structured in a way that enables testing the entire DS. ToC originated in computational models, and simulations offer a path to start SBD with the resources available and still make decisions, enabling better chances to learn and innovate the product. It is especially true in highly innovative projects below TRL-7, such as the application case presented in this Dissertation.

TRL less than 7 are projects in which designers are not certain about the path the project will take, which values the parameters will assume, and whether it will be viable, or the required performance will be achieved. This scenario is roughly inherent to any R&D project; however, at low TRL the uncertainties have a much more critical magnitude. It is complex to model discrete concepts and apply a decision matrix to decide what is best. Therefore, PBD is not a suitable strategy for these cases. SBD's nature of gradually building knowledge is ideal for highly innovative products since it allows developers not to commit to solutions without being sure of their viability.

ToC generated by mathematical and computational data provide information to bound the initial DS without compromise extensive portion of the budget with experimentation. Still regarding the balancing problem, another absence in the literature is guidelines for planning and conducting NDP activities and coordinating teams to achieve goals. It led to efforts to present solutions to discard or consider regions with better chances of success. Authors focused on advancing CS methods, assisted by computational tools. Some authors mention the LI as a second option but do not present details on how to decide or what to do with this information. Furthermore, works explore the Value of Information, which can be a first step toward procedures to control and decide on the amount and depth of experiments.

The general management of SBD passes through the coordination of PDCA short LC and IE, gathering knowledge to support decision-making toward development goals. Nevertheless, this is one of the least explored themes in the literature and one of the most important to enable the strategy. Some authors mention the possibility of hybrid development strategies integrating PBD and SBD, but it is necessary to establish links between domains and provide guidelines for this decision. The overall analysis of the literature provided the main gaps hindering SBD dissemination, which could be elicited in Chapter 2. The researcher believes that closing these gaps opens avenues for LPD in more application cases. Table 5.1 presents a comparison of the literature gaps and the advances of this Doctoral Dissertation.

Table 5.1. The literature gaps and the advances in this Doctoral Research

Literature gap		Doctoral Dissertation
1	Demonstrate the contribution of value deployment for the NDP	→ A model for value deployment based on QFD and its connection with TKDev, linking value, IE, and LC.
2	Demonstrate the generation and contribution of ToC during the NDP in the context of IE and LC	→ A model for generating model-based ToC and their input in TKDev.
3	Approach the evaluation of sets for filtering based on the criteria adopted during IE	→ Structure of the IE and TKDev storyboard suggesting the procedure for evaluating sets. ToC to support NDP.
4	Demonstrate how LC and IE are connected and present a method integrating them	→ TKDev approach.
5	Present a method for LC and IE management and execution;	→ RBM and TKDev approach.
6	Methods to decide on the LI of each part	→ Method for deciding on the LI and declaring it as a Multi-Criteria Sorting Problem.
7	Present a hybrid development strategy model integrating SBD and PBD	→ Model for hybrid development strategy, integrating SBD and PBD through CHTF and CUTF solutions.
8	Approach the participation of stakeholders and manufacturing in the NDP evidencing their contribution to DS reduction	→ DS propagation to all product levels, enabling to integrate manufacturing through evaluate concepts from production DS.
9	Presenting techniques to support decision-making regarding balancing DS with the resources available	→ Method for deciding on the LI and hybrid development strategy.
10	Model the knowledge capture, management, and storage in SBD	→ TKDev storyboard.
11	Present a comprehensive model for the product development flow in SBD	→ A model and process for SBD.

5.2. RESEARCH ACTION RESULTS

The PDP tackles intrinsic uncertainties related to deadlines and cost or the ability to meet CR efficiently. Highly innovative products add to this scenario the considerable lack of knowledge about the operation, applicability, technological suitability, lack of qualified suppliers for materials and parts, significant restrictions on human and financial resources, and issues related to the integrability of subsystems. The exploratory nature of SBD and its principles of keeping the DS open as long as possible, delaying decisions, prioritising the global over the local, and not committing to specific solutions make it the most suitable strategy for these products.

Models enabling the use of SBD in environments with such characteristics are absent in the literature, although crucial. Considering the application case of this research, it would not have been possible to explore the DS so extensively at the beginning of the development since the resources needed would have far exceeded the ones available for the MRU project. Strategies for balancing resources and still benefiting from SBD are fundamental. Even though computational tools were adopted, the DS was kept open, the global optimum was sought, and tests and experimentation were carried out for the most critical stages of development.

SBD promoted innovation and enabled the success of the development. Especially considering the lack of knowledge regarding the range of values the final parameters of the product would assume. The application case of this Doctoral Dissertation fits the LPD precepts since the lack of knowledge regarding the product jeopardises the ability of designers to choose the best alternative from a pool of solutions according to a PBD strategy (OLIVEIRA *et al.*, 2023b). Developing technological innovations means facing many uncertainties and risks, which demands a robust alignment toward value. Nevertheless, the support provided by the current literature is the house of quality applied to traditional management environments.

To enable SBD in highly innovative environments, a robust method for deploying value is necessary. QFD and the concept paper guided the development of the MRU. It is important to highlight that applying only the house of quality would not provide enough support for the project. Before 2016, when the research group adopted traditional management techniques, leaders perceived a lack of alignment between researchers contributing to the product design. Not only there was no formal value definition for each part of the product but also there was little integration between designers. It motivated the research group to seek novel approaches to conduct development activities (OLIVEIRA *et al.*, 2023b).

The LPD provided an environment favouring innovation and learning about the technology from scratch. It attended to the requirements of the project and enhanced subsystem integration. Nevertheless, the intricate character of subsystems and the necessity of precise synchronisation of parts would not be properly considered, if the focus was only on the system EC. It was necessary to advance in including subsystems' participation in value and understand the contribution of all parts to system performance.

Deploying value, identifying the critical parameters, and prioritising trade-offs at all product levels enabled delimiting DS and front-load the NDP with sufficient information to start evaluating alternatives and regions. The deployment of value formed the basis of analysis in every integration event. The team delimited the initial feasible regions and EC acceptable values through the QFD. Since engineers lack much information about parameters and operation ranges, many ECs were left without a range of values until knowledge was acquired to understand and establish the initial DS.

The highly innovative character of the product and resource limitations of the project led designers to adopt model-based ToC to guide the analysis of alternatives (see OLIVEIRA et al. 2023a). They identified feasible regions in ToC by representing the current range values of critical EC composing contradictions. Every change in DS during IE caused a change in the feasible regions in the ToC. The information obtained in QFD matrices provides an overview of the product challenges and relationships between subsystems. Designers identify the contradictions in the design based on the roofs of the matrices.

The triad cooling capacity, power consumption, and system cost were exhaustively studied by developers to deliver customer value. Outside that, the biggest concern was the synchronicity of AMR and MC to produce better operation conditions and achieve the highest refrigeration capacity possible. Designers studied the impact of AMR and MC by defining the relations between their most critical EC. Furthermore, subsystems generated and considered their trade-offs internally. They brought their ToC to justify decisions regarding discarding DS regions (OLIVEIRA et al., 2023a).

Exchanging such information in IE was positive since other subsystems offered a different perspective on the subject. Integrating manufacturing issues in the NDP is crucial since it enables considering a lean perspective on fabricability, quality, logistics, interchangeability of parts, robustness, and so on. The third and fourth level of QFD aims to deploy value until the production level to provide guidelines on the impact of manufacturing processes in delivering value. Connecting fabrication parameters with CR means understanding their contribution to deliver the product's required performance. It implies a complete alignment toward value from the design until the provision of the solution.

A lean enterprise is an organisation capable of creating this alignment not only door to door but in the total product lifecycle. Thus, deploying value for manufacturing levels is crucial for LPD. Generating third level matrices in the application case is complex in TRL-6 products. Analysing manufacturability is a challenge due to the originality of the technology application and suppliers. Nevertheless, understanding production issues and possibilities was fundamental for the project. It enabled the propagation of the feasible DS from the manufacturing level up to the system level, enhancing the NPD by discarding not only regions with poorer performances but also regions with manufacturing limitations.

The unprecedented application of technology opened an avenue for collaboration with magnetic materials research, aiding in understanding manufacturing parameters and processes for the MCM. Nevertheless, the scarcity of suppliers with expertise in producing MC posed a difficulty in defining parameters and processes. Designers investigated the possible fabrication paths for Permanent Magnets.

Estimating costs was a challenge for MC. The teams focused on obtaining the best overall performance to deliver to the AMR. Nevertheless, when the design was finished and sent to the supplier, the resulting cost exceeded by far the budget. It was a major shortfall that would be very difficult to be avoided due to the innovation degree of the project. The NDP acted in the project favour since knowledge enough was built to define countermeasures to diminish costs and still guarantee the refrigeration performance required for the product (see OLIVEIRA *et al*., 2022b).

Diminishing the cost of the subsystem demanded the reduction of magnet mass. The teams had a clear perspective on which parameters would be affected by it since value definition and the establishment of interrelations between critical parts enabled an understanding of the impact of the changes. Designers quickly adjusted the project to solve the problem without compromising deadlines. Even though the involvement of the supplier was difficult, SBD provided the capability to react to a major project setback.

Even though the application of SBD was resource-demanding at the first moment, it was possible to observe that the costs were offset by the gains obtained. First, the upward and downward propagation enabled the discarding of unfeasible DS regions based on manufacturing. It was observed that it has the potential to provide guidelines for the production process directly from the PDP. It also prevented testing unfeasible solutions, which would demand rework and waste of resources.

Adopting balancing strategies was crucial in this project. Unburdening the DS by removing regions that would most likely fail was not feasible due to the lack of knowledge and technological state-of-the-art. Since it was a new technology, never been applied in an industrial product like the MRU before, the developers did not have the knowledge necessary to discard regions from the DS. The remaining alternative was to remove subsystems from the SBD domain. Even though the MRU was an innovative product, it was easy to identify candidate subsystems.

Three main challenges permeated the development: the high cost of materials, the small team, and the scarcity of knowledge about the technology. The hybrid development model enabled the reduction of experiments, contributing to cost reduction. Subsystems developed according to PBD do not require the same number of experiments as SBD subsystems. Furthermore, it was possible to allocate more people to the SBD subsystems and fewer to the PBD, helping to balance the team and focus efforts on the critical parts of the product. Finally, SBD's exploratory and scientific nature enabled learning about the product from scratch without prior knowledge to support decision making.

Defining the LI enabled to focus efforts on the core of the product, i.e., on the design of the AMR and MC. The HS was developed as a CHTF solution since it is widely used in other products and technologies with the availability of components that deliver a wide range of operating points. Considering the complexity of changing the development strategy of a subsystem in an ongoing project is crucial to decide on the LI. In the case of the HS and its components, it would be easy to change from CHTF to a CUTF solution. Nevertheless, if changing is complex, one can consider a CUTF solution from the beginning.

The HEx presented a different scenario. Even though it is a widely used technology with market availability, the particularities of MR make HEx optimisation an advantageous option for the system. Consequently, the subsystem was developed as a CUTF solution. The innovation matrix provided an overview of the subsystems and their connections. The criteria were sufficient to identify the candidates for PBD and define the strategy for each subsystem. The development team found no difficulties in making the decision even though they did not have vast knowledge about the technology.

The decision regarding the LI was confirmed since there were no changes during the development. By alternative evaluation during IE, it was possible to choose a valve capable of operating at the frequency and mass flow rate following the requirements of the HS (see SANTOS et al., 2021a). Regarding the HEx, the customisation project was successfully coupled with the system. The customisation process was performed concurrently with the design of the MC and AMR (both under SBD strategies) and updated as the other subsystems advanced in their development. Mathematical models for the three components were coupled into a system model, and their impact on the performance was assessed. It supported the design to seek to minimise the cost and maximise efficiency (PEIXER et al., 2022c).

Monitoring the DS reduced the risks of not developing all the subsystems under the SBD umbrella. The choice of parameters to guide the verification of compatibility between the SBD and PBD domains is crucial. Critical parameters that affect performance, account for limitations in the design, and connect PBD and SBD subsystems are candidates. In the application case, the monitoring was guided by frequency, mass flow rate, and effectiveness.

Since experimentation would compromise the budget due to the elevated costs of raw materials, model-based ToC were generated. They contributed to several activities and supported decision-making during the design process. Through model-based ToC, it was possible to perform a screening in the DS at the beginning of the development, searching for regions presenting a higher probability of success. Furthermore, by focusing on these regions, it was possible to plan experiments according to the availability of resources. Thus, not only does model-based ToC enable the initial screening of alternatives, but also the SBD itself, since the initial screening balances resources and DS.

ToC are tools for knowledge generation, storing, sharing, and management. Through the application of model-based ToC, engineers were able to share simulation results and relevant information among teams, not only during IE but also during LC. Filtering activities during the NDP were based on ToC. They assisted in presenting the current DS of the system and verifying which solution alternatives were out of the feasible area. It contributes to building an agreement regarding the current DS.

The determination of the most crucial contradictions and design parameters was performed based on the results of the QFD matrices. The decision regarding which ToC to generate depended on the availability of resources and knowledge-gaining expectations. In the application case, the system impact and availability of data and resources formed the criteria for planning ToC drawing.

Physics-based and Math-based ToC were generated during the project. The physical and mathematical background consisted of fluid dynamics, thermodynamics, heat transfer, and magnetostatics. The assumptions and the development of the models of the subsystems were guided by the phenomena involved in each subsystem. ML methods were adopted to reduce the computational cost of simulations. The coupling process to constitute system performance metrics was based on geometric and operating interactions.

Building the simulation environment, simulating, drawing, and observing the behaviour of parameters enabled the developers to identify tendencies and gain knowledge. Predicting the system behaviour is a challenge since innovative products, such as the MRU, are based on very little previous knowledge. Before the simulations, developers expected the system to operate with higher values of mass flow rate, for example. Nevertheless, the simulations presented not only a drop in the cooling capacity but also a surge in the pressure drop. It affected the development of the system by reducing the expected operating mass flow rate, which had to be compensated by a design parameter of another subsystem, the radius of the MC.

Studying the behaviour of the system and subsystems under varying conditions and drawing model-based ToC brought extensive knowledge to develop the product. The models for each subsystem based on their physical constitutive laws and governing equations and further validation with experimental results provided accuracy and flexibility for the simulations, reducing the necessity of assembling several prototypes. When proper mathematical modelling is applied, considering the phenomena and couplings involved in the subsystems, the deviations are within acceptable margins for screening the initial design regions.

Simulation environments enable the comparison of parameters related to different subsystems. The NDP is based on four premises: infeasibility, unmet requirements, solution proven inferior, and incompatible among subsystems. Even though compatibility is one of the three principles of SBD, few are demonstrated in the literature on how to compare and narrow based on the intersection of DS. Model-based ToC assist in intersecting subsystems since it is easier to perform the superposition of DS in computational environments. Furthermore, performing experiments to compare parameters from different subsystems is quite complex.

The subsystem integration is a matter in SBD, not only due to the compatibility principle, but for synchronising activities, disseminating knowledge, and building the agreement on the current DS. Model-based ToC assisted in communication, especially regarding understanding the impact of certain local decisions on MRU's overall performance. An example is the behaviour of the mass flow rate. From the perspective of the hydraulic management subsystem, it is advantageous to operate at the lowest possible values of this parameter. Nevertheless, it was demonstrated that the AMR demands a minimum value of this parameter for the system to operate within the required performance. Similarly, from the MC perspective, lower radius values are favourable for its performance but are also restricted by the demands of the AMR. Thus, the hydraulic management and MC subsystems must guarantee the operation of determining design parameters within the range values specified by the system requirements.

The ToC generated, simulations, mathematical equations, and databases formed a knowledge background for future projects that can further develop the application of the technology. Model-based ToC and its data were used during development as an instrument to generate, disseminate, and store knowledge. Especially during IE when the main results of simulations and ToC were used to demonstrate the status of the DS and technical knowledge of the product.

Many contributions arising from the model and process for the SBD in the application case were fundamental for developing the product. However, from the perspective of the researcher and the development team, the biggest impact was caused by TKDev. Through the KC cycles and IE, project risks decreased, integration between teams increased, information sharing contributed to the alignment of subsystems, and managing possibilities improved in the project.

Before LPD, the research group held monthly or bimonthly meetings, allowing large deviations to occur within subsystems before they could be corrected. It generated many problems such as rework or risks of not achieving product performance. Increasing in the frequency and a better structure for the meetings represented a managerial shift for the group, making the development more rhythmic and integrated. Furthermore, the shift from timelines to DRs allowed developers to manage their work and learn not only about the product but about timing and how to better plan cycles.

This trend became clear with the evolution of the key management indicators, in which the teams significantly improved planning accuracy. With time and learning, fewer and fewer teams were surprised by setbacks or results that differed from what was planned. In addition, the inclusion of developers with previous experience in kata showed that mastering the storyboard also contributes to more accurate planning.

The possibility of connecting coaching cycles with integrative events, DR, and current DS created a cadence for development and ensured the alignment of subsystems for the value and expected results of the project. The set of storyboards with all curves, experiment results, and stored learning formed a knowledge base for the group that serves as a reference in future projects. In this way, all teams have a cycle-by-cycle report of everything that was done and learned in each step of the project.

5.3. SOCIAL, ECONOMIC, AND MANAGERIAL IMPLICATIONS

The managerial insights outcoming from this work assists decision-makers in overcoming barriers to SBD adoption. First, to the best of the researcher's knowledge, this is by far the most complete demonstration of the SBD in the literature. First, any publication was found expanding matrices beyond the house of quality except for the work of Milcic, Borkovic, and Vucina (2017). The methodology provides the most benefits when adopted completely, deploying value to all product levels. Second, balancing methods focus on CS but ignore the necessity of using computational tools and a hybrid development approach to expand SBD. Third, the backbone of the NDP is not explored to such an extent as in this Doctoral Dissertation.

This background provides a clear perspective of the benefits and implementation paths for SBD. The demonstrated results can encourage practitioners to look at QFD from new lenses that go beyond the system level. Providing guidelines to better address and manage value is the path to products with a better market fit. Furthermore, DS propagation opens avenues for manufacturing participation in the NDP.

This contribution provides the basis for lean manufacturing integration with LPD since it starts with a product that embraces its precepts, including logistics, continuous flow, quality, product lifecycle, and so on. The QFD third and fourth levels have the potential to integrate value and fabrication, enabling managers to design and prepare products and production to deliver maximum value.

It is one of the first applications of LPD in highly innovative projects. The literature on the subject approaches products with a consolidated knowledge background. Projects with high innovation degrees can benefit from learning orientation, later decision making, and the experimenting character of SBD. Applying its concepts in such environments provides better chances of success and innovation. Thus, this application provides guidelines for LPD and SBD in new environments.

Advancing knowledge in SBD and expanding its adoption means designing solutions with a higher innovation chance and better market fit since it is oriented to value. This research is an initial step toward new management models and approaches to break barriers for LPD in organisations. It implies fostering innovation and delivering more value for society, customers, and organisations. Furthermore, innovative solutions seek to offer better conditions of application, costs, and footprint. SBD can be integrated with green approaches to more environmentally friendly products, such as the case of the MRU.

CHAPTER 6

CONCLUSION

This Chapter concludes the work by providing the main highlights and learning from the Research process. Section 6.1 presents the conclusion of the research, and section 6.2 provides future studies recommendation. This research is the first step toward managerial models and processes for SBD and seeks to raise the literature awareness for problems and hindering factors the industry faces when applying LPD. One of the greater gains outcoming from this research is to shift academic focus, stimulating a comprehensive view of the NDP and proposing implementation-oriented efforts to disseminate SBD.

6.1. CONCLUSION OF THE RESEARCH

The studies on SBD showed that among the strategies of solution convergence for product development, SBD 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. These factors must be taken into consideration in the development of models and frameworks for SBD. Based on the SBR results, any work addressed SBD broadly since none approached 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.

Research authors consistently agree on the lack of models supporting SBD adoption. The use of ToC, manufacturing, supply chain involvement, LC, IE, and narrowing down criteria application is widely mentioned as practical SBD enablers, but they remain scarce in the literature. Although prototyping, testing, and experimentation are addressed as key tools to foster decision making, these practices are rarely explored. Based on the main findings, it was identified many gaps hampering SBD implementation efforts, and even though the superiority of SBD over traditional product development approaches is known, it makes it difficult for development teams to adopt this strategy.

The model and processes proposed in this Doctoral Research focused on filling the main gaps for advancing knowledge in SBD. The development and implementation of the model enabled to understand how critical the managerial perspective is to conduct LPD. Even though many were presented in the literature regarding supporting tools, without a consolidated method for orchestrating teams to apply those tools, designers would not be able to adopt SBD. The NDP of the MRU demonstrated that the protagonist is value deployment and alignment and planning target knowledge conditions to support decision making and not in specific tools related to the strategy.

It was clear to see, from a manager's perspective, that with the state-of-the-art before this Dissertation, it would be very hard or at least very unlikely to succeed in SBD and LPD. It was only due to the research and discovery process, supported by the TKDev development that the research group was able to organise for NDP. Furthermore, LPD fits the application case since the lack of knowledge regarding the product jeopardises the ability of designers to choose the best alternative from a pool of solutions according to a PBD strategy.

Designing highly innovative products means facing a lack of previous knowledge about the technology, unqualified suppliers for materials and parts, significant resource restrictions, and integrability challenges. The exploratory nature of SBD and its principles of keeping the DS open as long as possible, delaying decisions, prioritising the global over the local, and not committing to specific solutions make it the most suitable strategy for these products. Developing technological innovations means facing uncertainties and risks, which demands a robust alignment toward value. Nevertheless, the literature gives little support presenting mostly the house of quality applied to traditional management environments.

The value deployment and definition model proposed in this Dissertation supported the development of the MRU by adopting QFD, serving as a beacon to guide design efforts. Exchanging value information in IE was positive since it stimulated the discussion and suggestions from different subsystems on how to learn and plan experiments and simulations. Deploying value, identifying the critical parameters, and prioritising trade-offs at all product levels enabled delimiting DS and front-load the NDP with sufficient information to evaluate alternatives and regions.

The lean design process of a one-of-a-kind system, with few comparable prototypes, presenting the challenges of a high innovation level product was not documented in the literature thus far, except for the master's Thesis preceding this Research. SBD implementation is hindered by the high number of resources necessary to perform the NDP. One of the possibilities to save resources is designing based on previous projects and prior knowledge, performing fewer experiments, and prototyping. Nevertheless, environments of innovation have several resource constraints and very little prior knowledge. Adopting a hybrid development strategy enables obtaining the benefits of SBD in the face of significant resources limitation.

The proposed hybrid method assisted in the implementation of SBD in environments subject to major financial and human resources constraints. Models to screen alternatives and evaluate DS balance the resources with the DS. Nevertheless, in innovation, the prior knowledge is very little, and developers often have no idea at which point the subsystems will operate. Therefore, it is necessary to advance in hybrid development strategies. Combining SBD and PBD is the way to balance resources and innovation. Developing products entirely based on the SBD strategy is quite costly, which may hinder its adoption. Therefore, this research is a step toward disseminating SBD.

The hybrid model can be managed by defining the LI intended for each subsystem of the product. Nevertheless, most of the works in the literature neglect this stage of product development or address it superficially. Even with little knowledge about the product and its subsystems, it was possible to classify them into PBD and SBD, assisted by the proposed matrix. Thus, the HEx was classified as CUTF, the HS as CHTF, and the AMR and MC as SBD solutions. Resources were focused on the last two subsystems, while the first two were chosen or customised according to the development. The innovation matrix provides a guide for decision-making on the LI of the subsystem and the classification of the solution in CHTF, CUTF, or SBD, enabling the proper allocation of project resources.

Integrating the two strategies means matching the narrowing of the DS with the possibilities of customisation or the point of operation of existing solutions. The compatibility between SBD and PBD was monitored during the IE. Model-based ToC were crucial for SBD during the development of the MRU. Validated mathematical models enabled to overcome the lack of solid background and resource limitations that hindered the development of knowledge-based ToC. Model-based ToC assisted in knowledge management, DS agreement, narrowing, learning about the product, and parameters performance study due to their capacity to provide fast and accurate predictions for the performance of systems and subsystems.

The risks and deviations associated with the models were quantified, thus enabling the use of model-based ToC in the design process. Considering the MRU, it would not have been possible to apply SBD for exploring the DS so extensively at the beginning of the development would have far exceeded the resources available for the project. Even though computational tools were adopted, the DS was kept open, the global optimum was sought, and tests and experimentation were carried out for the most critical stages of development. Thus, model-based ToC based on experimentally validated physical and mathematical models enables SBD adoption in the design process of highly innovative products.

The learning and discovery process led by TKDev during the project demonstrated that the coaching session not only gave the CE a clear overview of the status of the project at all product levels but promoted integration among teams. Sessions not only provided an environment to share results and justify DS updating but also to discuss and direct efforts. During IE, other subsystems recommended actions or asked for assistance when facing difficulties. The adaptation proposed in the model of Rother (2014) enabled its application in LPD.

Matching SBD with organisations reality means supporting decisions regarding balancing resources and DS, managing value and connecting it with the analysis of alternatives in a practical manner, assisting in stakeholders' integration, considering DF-X factors, risk assessment and value of information, and so on. Practical models and frameworks for SBD must focus on eliminating such barriers and stimulate practitioners to migrate from traditional management techniques to embrace LPD.

The lean enterprise starts with a well-structured learning-oriented R&D. One of the main learnings of the researcher is to understand that lean manufacturing starts in an LPD. Without a formal and effective manufacturing integration during product development, several problems will propagate to other phases of the product lifecycle. Lean New Product Introduction must rise as the new research trend in the field and advance along with LPD to foster innovation and create a better society with more value-added and innovative products.

The value deployment coming from initial design stages must be propagated to lean manufacturing, providing a clear understanding of which processes and production parameters are critical for value and which aspects of the product are more perceived and wanted by customers. It can direct efforts of continuous improvement effectively focusing on value, instead of just reducing waste without an in-depth understanding of the impacts of actions on customers. Furthermore, many design decisions will make lean production easier or harder.

6.2. FUTURE STUDIES

This Doctoral Dissertation represents a pioneering effort to a referential managerial work for SBD. Nevertheless, much is still necessary to further explore. The main contributions and gaps found in the literature and the discoveries of this research enabled the recommendation for future works. The literature and research community must pave the way for new more detailed, robust, and implementation-oriented works, providing the tools for spreading SBD and its benefits. Based on the conclusions, the future works recommendations are:

1 Expand the application of the value deployment focusing on quality and production levels;

2 Apply the model and process for SBD in projects with other technological levels than TRL-6;

3 Apply and understand the impact of the model in complex products with more consolidated technologies;

4 Develop supporting tools and managerial approaches for lean new product introduction, establishing clear guidelines connecting LPD and lean manufacturing;

5 Advance in using DS propagation for including new levels of abstraction and stakeholders in the NDP, especially production, defining better managerial decisions regarding this subject;

6 Connecting DS propagation with DS representation methods and designers' preference;

7 Advancing in guidelines for managerial decision about balancing resources and DS, including mathematical modelling and tools for assisting in deciding balancing techniques, especially controlling the depth and number of experiments focusing on risk management in SBD;

8 Advance in modelling the LI as an MCSP providing guidelines matching problem size, complexity, and approaches;

9 Methods for structuring manufacturing teams and their participation in the NDP;

10 Advancing in connecting QFD and new product introduction or application engineering;

11 Test and research the TKDev in projects with complex organisational structure with several subsystems and teams to grasp its impact and advance in its modelling;

12 Study, from a cost perspective, the hybrid development strategy, and its potential to enable SBD under severe restrictions;

13 Further research in methods to assist decision-making and computational tools for integration between PBD and SBD.

14 Methods to decide on the size of the DS based on the LI of subsystems;

15 Applying the model-based ToC in other environments, not only in different innovative products and technologies but for traditional products to verify the potential to assist in planning and knowledge gained through simulation;

16 Propose techniques to control risks and deviation in model-based ToC, by balancing the use of real and simulated experiments.

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APPENDIX A

MODELS AND FRAMEWORKS FOR SET BASED DESIGN

	Inputs								Narrowing-down process						Outputs
	Value research and definition	Value deployment	CS and alternatives evaluation	DS representation	IPT and organisational structure	Initial DS definition	Planning for SBD	Knowledge use and management	Steps and activities for NDP	Integration events	Trade-off curves	Learning cycles	Supporting and computational tools	Manufacturing integration	Final set and chosen-to-fit solutions
Lin (1992)				●		●									
Hernández-Luna; Wood (1994)				●									●		
Ward *et al*. (1995)									●						
Lee (1996)			●	●		●			●						
Bernstein (1997)									●						
Nahm; Ishikawa (2004)				●					●				●		
Oppenheim (2004)									●						
Fernández (2005)		●	●	●		●			●				●		
Terry (2005)													●		
Nahm; Ishikawa (2006)				●					●						
Kao (2006)		●							●		●				
Bhushan (2007)	●	●				●			●				●		
Pessôa *et al.* (2007)							●								
Madhavan *et al.* (2008)		●							●						
Malak (2008)													●		
Avigad; Moshaiov (2009)			●			●									
Inoue; Ishikawa (2009)				●					●				●		
Frye (2010)					●	●	●		●				●		●
Hernández-Luna *et al.* (2010)				●					●						
Martínez (2010)							●								
Schäfer; Sorensen (2010)			●												
Raudberget (2010a)									●						
Raudberget (2010b)									●						
Furian *et al*. (2011)								●					●		
Gray (2011)				●					●				●		
Mascitelli (2011)	●	●					●			●		●	●		
Mckenney *et al.* (2011)					●	●			●						●
Mebane *et al.* (2011)	●	●					●		●						●
Raudberget (2011)			●						●				●		
Khan *et al.* (2011)	●	●			●	●	●		●		●				●
Kerga; Khan; Arias (2012)		●							●						
Kerga; Taisch; Terzi (2012)		●							●					●	●
Wasim (2012)													●	●	
Wasim *et al*. (2013)													●	●	
Al-Ashaab *et al*. (2013)	●		●		●	●			●						
Autzen (2013)	●	●	●				●		●						
Inoue *et al.* (2013)									●				●		

Kerga *et al.* (2013)	●	●					●				●				
Maksimovic (2013)								●							
McKenney (2013)				●					●						
Kennedy *et al.* (2014)	●								●						
Kerga *et al.* (2014)	●	●					●				●				
Levandowski *et al*. (2014a)		●							●						
Levandowski *et al*. (2014b)		●							●					●	
Qureshi *et al*. (2014)													●		
Raudberget *et al.* (2014)		●													
Araci *et al*. (2015)									●		●				
Diels *et al*. (2015)							●								
Dobrovolskyte (2015)	●	●	●		●		●	●	●						
Kim (2015)														●	
Raudberget *et al.* (2015)	●	●							●						
Raudberget (2015)	●	●							●						
Rosen (2015)				●					●				●		
Sasaki; Ishikawa (2015)				●					●				●		
Souza; Borsato (2015)									●						
Amine *et al.* (2016)									●				●		
Araci *et al.* (2016a)									●		●				
Araci *et al.* (2016b)									●		●				
Chan (2016)			●						●						
Dafflon *et al.* (2016)									●				●		
Schuh; Rudolf; Luedtke (2016)	●	●	●												
Schulze (2016)			●		●										
Ström *et al.* (2016a)	●								●						●
Ström *et al.* (2016b)	●								●						●
Amine *et al*. (2017)			●												
Ammar *et al.* (2017)	●	●							●						
Oliveira (2017)	●	●					●			●		●			
Araci *et al.* (2017)	●					●			●		●				
Essamlali *et al.* (2017)			●				●	●							
Johanesson *et al.* (2017)	●	●							●						
Maulana *et al.* (2017)	●		●				●		●						●
Parker *et al.* (2017)			●			●			●						
Stolt *et al*. (2017)														●	
Toche (2017)	●		●	●					●				●		
Toshon *et al.* (2017)						●			●				●		
Oliveira *et al.* (2017)	●	●					●		●			●			
Ammar *et al*. (2018)									●		●			●	
Borchani *et al*. (2018)									●				●		
Lermen *et al.* (2018)	●	●			●	●	●							●	●
Oliveira *et al.* (2018)	●	●					●		●			●			
Rapp *et al.* (2018)									●				●		
Small (2018)	●								●		●				
Specking *et al.* (2018)	●								●		●				
Wade (2018)									●						
Whitcomb; Hernandez (2018)									●						
Ammar *et al*. (2019a)	●	●							●		●				
Ammar *et al*. (2019b)	●	●							●						
Ammar *et al*. (2019c)	●	●							●						
Bertoni; Bertoni (2019)			●												
Borchani *et al*. (2019)	●	●							●					●	
Buchanan *et al*. (2019)									●						
Fitzgerald; Ross (2019)													●		
Georgiades *et al*. (2019)									●				●		
McNabb *et al*. (2019)													●		
Müller *et al.* (2019)	●	●	●						●						

Parnell *et al.* (2019)	●								●		●				
Rempling *et al*. (2019)									●						
Saad *et al*. (2019)									●						
Shallcross *et al*. (2019)									●						
Siiskonen (2019)	●	●							●					●	
Araci *et al*. (2020)								●			●				
Blindheim *et al.* (2020)			●												
Chen *et al*. (2020)					●		●		●						
Ishikawa; Sasaki (2020)				●					●				●		
Jonkers; Shahroudi (2020)													●		
Landahl *et al*. (2020)	●	●							●					●	
Lu *et al.* (2020)							●								
Mohsin *et al*. (2020)									●		●				
Pillai *et al*. (2020a)			●												
Pillai *et al*. (2020b)			●												
Rapp *et al.* (2020)									●				●		
Santos *et al*. (2020)	●														
Shallcross *et al.* (2020b)									●						
Stumpf *et al*. (2020)													●		
Suwanda *et al.* (2020)								●							
Zhong; Dockweiler (2020)								●		●		●			
Araci *et al*. (2021)								●	●		●				
Ortiz (2021)				●											
Shallcross *et al*. (2021a)									●						
Shallcross *et al*. (2021b)													●		
Shallcross *et al.* (2021c)													●		