Titre: Title:	Set-Based Prototyping in the Context of the Configurable Virtual Product: The Construction of the Learning Value Streams (LVS) Model
Auteur: Author:	Luc Boris Toche Fumchum
Date:	2017
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Toche Fumchum, L. B. (2017). Set-Based Prototyping in the Context of the Configurable Virtual Product: The Construction of the Learning Value Streams (LVS) Model [Thèse de doctorat, École Polytechnique de Montréal]. PolyPublie. https://publications.polymtl.ca/2910/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/2910/
Directeurs de recherche: Advisors:	Clément Fortin, & Robert Pellerin
Programme: Program:	Génie mécanique

UNIVERSITÉ DE MONTRÉAL

SET-BASED PROTOTYPING IN THE CONTEXT OF THE CONFIGURABLE VIRTUAL PRODUCT: THE CONSTRUCTION OF THE LEARNING VALUE STREAMS (LVS) MODEL

LUC BORIS TOCHE FUMCHUM

DÉPARTEMENT DE GÉNIE MÉCANIQUE

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

THÈSE PRÉSENTÉE EN VUE DE L'OBTENTION

DU DIPLÔME DE PHILOSOPIAE DOCTOR

(GÉNIE MÉCANIQUE)

DÉCEMBRE 2017

UNIVERSITÉ DE MONTRÉAL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

Cette thèse intitulée :

SET-BASED PROTOTYPING IN THE CONTEXT OF THE CONFIGURABLE VIRTUAL PRODUCT: THE CONSTRUCTION OF THE LEARNING VALUE STREAMS (LVS) MODEL

présentée par : TOCHE FUMCHUM Luc Boris

en vue de l'obtention du diplôme de : Philosophiae Doctor

a été dûment acceptée par le jury d'examen constitué de :

M. LAKIS Aouni, Ph. D., président

M. FORTIN Clément, Ph. D., membre et directeur de recherche

M. PELLERIN Robert, Ph. D., membre et codirecteur de recherche

M. BALAZINSKI Marek, Docteur ès sciences, membre

M. RIVEST Louis, Ph. D., membre externe

DEDICATION

To my grandfather, Joseph Toche.

ACKNOWLEDGEMENTS

I would like to extend my sincere gratitude to a number of people for their support during these years of research. First and foremost to my supervisors, Professor Clément Fortin and Professor Robert Pellerin, for their insights, continuous encouragement, guidance and patience.

I'd also like to thank all my colleagues at P&WC, particularly participants in the Product Lifecycle Management (PLM) transformation program. I've had the extraordinary opportunity over these years to work with a number of talented young and experienced engineers and employees who contributed to form many of the concrete ideas to the management and execution of product development activities at P&WC, and furthermore to this thesis. A particular note of appreciation is due to all students I supervised at P&WC for their fresh insights, teamwork and dedication.

I'm grateful to Dr. Gregory Huet and Dr. Grant McSorley for their unwavering support and constructive engagement while collaborating on conference and journal papers that we either submitted, presented or published. I would also like to thank all students I supervised for their openness and participation during my involvement in the Product Development and Systems Integration (PDSI) project at Polytechnique. On a different note, I must acknowledge the Mechanical Engineering department and the whole personnel at École Polytechnique de Montréal for their kind support and guidance.

Finally much of this work would not have been possible without the support from family including Conilh de Beyssac, and inspiration from my parents.

Marie, Hazaël, Wilona, this last year has not been easy for us. There are simply no words that can describe to what extent you made all of this possible.

RÉSUMÉ

La présente thèse de doctorat est le résultat de sept années de recherche intervention dans les domaines de la conception et du développement de produits suivant le paradigme lean en aérospatial. Cette recherche action est motivée par la nécessité de développer les connaissances ainsi que les outils appropriés pour le développement de produits suivant l'approche lean (LPD pour Lean Product Development) et en particulier celle de l' « ingénierie concourante fondée sur les options de conception » (SBCE pour Set-Based Concurrent Engineering) en aérospatial. Une telle nécessité se justifie par les facteurs socioéconomiques du 21ème siècle qui imposent des approches de conception et développement toujours plus robustes, résilientes, réactives, flexibles, innovantes et adaptables face aux fluctuations du marché et à la demande des consommateurs qui évolue rapidement, ceci afin de permettre aux compagnies de demeurer compétitives.

L'objectif principal de la recherche, au vue de tels impératifs, est d'identifier, pour ensuite développer et intégrer dans un modèle holistique, les aspects, les caractéristiques et les catalyseurs essentiels des approches LPD et SBCE appliquées à l'industrie aérospatiale de façon à supporter l'implémentation à grande échelle de telles approches, et ce, dans une optique sous-jacente de gestion de cycle de vie du produit (PLM pour Product Lifecycle Management).

La planification et l'exécution du projet de recherche sont réalisées en respectant une méthodologie éprouvée en conception (DRM pour Design Research Methodology) afin de focaliser les résultats sur l'avancement des connaissances et de la pratique du LPD et SBCE en tant qu'approches de conception. La recherche apporte en conséquence des contributions majeures à ces champs d'étude tout en prescrivant une méthodologie de transformation des processus et outils de développement de produits dans l'industrie par le biais de l'implémentation du modèle de « chaines de valeur apprenantes » (LVS pour Learning Value Streams).

Plus en détails, les contributions aux avancées scientifiques et pratiques dans le domaine vont comme suit : **(1)** La proposition d'un nouveau cadre d'analyse de la littérature SBCE ainsi qu'une méthodologie de revue systématique fondée sur des données probantes; **(2)** L'avancement des connaissances théoriques et pratiques du LPD et SBCE des aspects les plus généraux aux plus significatifs; **(3)** L'avancement des connaissances théoriques et pratiques sur la modélisation et les structures de produit requises dans une optique de gestion de cycle de vie du produit suivant le paradigme lean; **(4)** La proposition d'une nouvelle méthodologie, incluant l'introduction d'une nouvelle structure de produit dédiée aux activités de prototypage et tests, afin de permettre la collaboration transdisciplinaire requise dans le contexte de gestion de cycle de vie du produit; **(5)** La proposition d'un nouveau domaine « existentiel » complétant les domaines fonctionnel, technologique et physique connus, afin de construire un cadre adéquat pouvant combler les manques relatifs à la modélisation et aux structures de produit qui concernent les configurations testées ou en service, ainsi que leur retraçage sur la base de composants identifiés par numéros de série; **(6)** La construction d'un modèle multi-domaines englobant des structures de produit complémentaires et configurées (CCS pour Configurable Complementary Structures). Ce modèle est adapté au déploiement du SBCE dans un contexte mature de gestion de cycle de vie du produit. Enfin, **(7)** L'extrapolation du modèle CCS au modèle holistique LVS qui fournit ainsi un cadre aussi bien théorique, conceptuel que pratique de transition de la conception et développement traditionnelle à celle lean avec le SBCE comme socle. Le nouveau modèle LVS s'inscrit dans des contextes d'implémentation compatibles avec la gestion de cycle de vie du produit telle qu'elle évolue dans l'industrie. La proposition d'un nouveau domaine « existentiel » ainsi que le modèle CCS dans son entièreté constituent donc les contributions majeures de la thèse, tandis que le modèle LVS est dépeint dans une optique de consolidation préliminaire, d'amélioration continue et de support pour de futurs travaux de recherche.

Mots-clés : lean, développement de produits, set-based concurrent engineering, variabilité, architecture de produit, modélisation de produit, gestion de la configuration, gestion du cycle de vie du produit, aérospatial, maquette numérique, prototypage.

ABSTRACT

The work reported in this thesis is the result of seven years of participatory action research in the field of Lean Product Development (LPD) in aerospace engineering. This research is motivated by the necessity to develop understanding and support for practical implementations of lean product development and especially Set-Based Concurrent Engineering (SBCE) in industry. Such necessity is justified by 21st century compelling socioeconomic factors that demand robust, resilient, responsive, flexible, innovative, adaptable and lean product development processes in order for companies to stay competitive in rapidly changing markets.

The main purpose of the research is to identify and develop the essential SBCE and LPD aspects, characteristics, features and catalysts as they relate to aerospace large-scale industrial product development in order to form a holistic model that can support practical implementations of LPD in industry from a product lifecycle perspective.

A design research methodology (DRM) is used for planning and executing the design research project while ensuring that focus is placed on achieving progress with regards to understanding and implementation of SBCE and LPD as Design practices. As a result, this thesis work provides substantial contribution to understanding of LPD and SBCE and furthermore, entails valuable proposal for the practice in industry through the CCS model and the construction of the Learning Value Streams (LVS) model.

Major contributions to the advancement of scientific knowledge and practice in the fields are as follows: **(1)** The proposal of a new SBCE dual analysis framework combined with an evidence-based systematic review methodology; **(2)** The advancement of theoretical and practical understanding of LPD and SBCE from the larger to the most significant aspects; **(3)** The advancement of theoretical and practical understanding of product models and product structure progression requirements for lean product lifecycle management; **(4)** the proposal of a new methodology, including new *as-tested* structure to support cross-collaboration during prototyping and testing in lifecycle management contexts; **(5)** The proposal of a new *existential* domain alongside the functional, technological and physical domains in order to address the lack of product modelling constructs and methodology when it comes to service or as-tested configurations, hardware testing transactions and prototype information tracking on the basis of serialized components; **(6)** The construction of the multi-domain Configurable Complementary Structures (CCS) model for practical implementations of SBCE in lifecycle management contexts, and finally; **(7)** The extrapolation of CCS to LVS to form a holistic model that can support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective. The new *existential* domain and the overall CCS model can be considered the main outcomes of the thesis, while LVS represents a path towards continuous research and improvement of LPD implementation in a lifecycle perspective.

Keywords: lean product development, set-based design, set-based concurrent engineering, variability, product architecture, product modelling, configuration management, product lifecycle management, aerospace engineering, digital mock-up, prototyping.

TABLE OF CONTENTS

DEDICATION III

ACKNOWLEDGEMENTS IV

RÉSUMÉ V

ABSTRACT VII

TABLE OF CONTENTS IX

LIST OF TABLES XII

LIST OF FIGURES XIII

LIST OF SYMBOLS AND ABBREVIATIONS XVII

CHAPTER 1 INTRODUCTION 1

1.1 Background and research motivation 1

1.2 Thesis structure 5

CHAPTER 2 LITERATURE REVIEW 8

2.1 Genealogy of Lean Product and Process Development 9

2.1.1 From Lean Production to Lean Product Development 9

2.1.2 Origins of Lean Product Development and evolution 13

2.2 Set-based Concurrent Engineering (SBCE) in the literature and industry 26

2.2.1 SBCE Background 27

2.2.2 A new SBCE systematic review framework 31

2.2.3 Synthesis 52

2.3 Conclusion 73

CHAPTER 3 METHODOLOGY 76

3.1 Research questions and objectives 76

3.2 Classification of the design research 78

3.3 Research methodology 83

3.3.1 Research Clarification 84

3.3.2 Descriptive Study I 84

3.3.3 Prescriptive Study 86

3.3.4 Descriptive Study II 88

3.4 Conclusion 92

CHAPTER 4 DESIGN PROTOTYPING AND THE DIGITAL PRODUCT INFORMATION 94

4.1 Prototyping activities in SBCE 94

4.2 Prototypes in engineering design 98

4.2.1 Traditional prototyping 99

4.2.2 Full virtual prototyping and limitations 103

4.2.3 Integration of physical and virtual prototypes 105

4.3 Digital product information for prototyping during the PDP 109

4.3.1 Characteristics of information in PLM 112

4.3.2 Complementary product structures for set-based prototyping 121

4.4 Conclusion 136

CHAPTER 5 CONSTRUCTION OF THE LEARNING VALUE STREAMS (LVS) MODEL 139

5.1 Prelude 139

5.2 Multi domain views in engineering design 142

5.3 Product models for SBCE industrial implementation 148

5.4 The Configurable Complementary Structures (CCS) model 153

5.5 Extrapolation to the Learning Value Stream (LVS) model ... 159
5.5.1 Set-based convergence ... 160
5.5.2 Extrapolation ... 162
5.6 Conclusion ... 168
CHAPTER 6 PRODUCT STRUCTURING PILOT SIMULATION ... 170
6.1 Aircraft engine firewalls ... 171
6.2 Simulation scenario and context ... 173
6.3 Conducting the simulation ... 180
6.3.1 Working in the technological domain ... 181
6.3.2 Working in the physical domain ... 187
6.3.3 Working in the existential domain ... 193
6.4 Conclusion ... 195
CHAPTER 7 CONCLUSION AND RECOMMENDATIONS ... 199
REFERENCES ... 209
DISCLAIMER ... 244

LIST OF TABLES

Table 1.1: Thesis chapters in relation to the design research methodology (DRM) 6

Table 2.1: Production system characteristics (Krafcik, 1988) 10

Table 2.2: Number of hits per keyword combination 41

Table 2.3: Category 5 SBCE publications 53

Table 3.1: Thesis chapters in relation to DRM sequence..90

Table 4.1: Development projects categories: Guidelines for prototyping and exploration. Adapted from (Ward & Sobek, 2014) 98

Table 4.2: Properties of typical physical prototypes categories. Adapted from (Ulrich & Eppinger, 2012)..101

LIST OF FIGURES

Figure 1.1: Design research methodology. Adapted from (Blessing & Chakrabarti, 2009)...........5

Figure 1.2: Correlation between the thesis chapters and the components of the proposed model...6

Figure 2.1: Literature review approach 8

Figure 2.2: Three models of product development 15

Figure 2.3: Phase-function view of a generic product development process. Adapted from (Ulrich & Eppinger, 2012)...19

Figure 2.4: Various models of LPD 25

Figure 2.5: Point-based approach to the design of a complex product. Adapted from (Ward et al., 1995)...27

Figure 2.6: Set-based approach to the design of a complex product. Adapted from (Bernstein, 1998)...28

Figure 2.7: Set-based design process analysis framework 38

Figure 2.8: Research paradigm analysis framework. 40

Figure 2.9: Distribution of Category 1-5 publications (relevant to SBCE) 42

Figure 2.10: Age profile of Category 1-5 publications 45

Figure 2.11: Medium of publication of Category 1-5 research work by year..............................47

Figure 2.12: Distribution of Category 1-5 journal publications..48

Figure 2.13: Category 1-5 journal Total Cites 49

Figure 2.14: Category 1-5 journal Impact Factor (5-year Impact factor: 2010-2015)..................50

Figure 2.15: Category 1-5 journal Eigenfactor score..52

Figure 2.16: Distribution of the Cat-5 publications by SBCE analysis segments.........................55

Figure 2.17: Distribution of the Cat-5 publications by Research paradigms and methods...........58

Figure 2.18: Enhanced Function Means (E-FM) and Configurable Component (CC) framework. Adapted from (Johannesson & Claesson, 2005). 70

Figure 3.1: Classification of Design Science. Adapted from (Hubka & Eder, 2012a) 79

Figure 3.2: Research paradigm....82

Figure 3.3: A Methodology for conducting design research. Adapted from (Blessing & Chakrabarti, 2009)....83

Figure 3.4: Descriptive study I structured focus group dashboard 85

Figure 3.5: Correlation between the thesis chapters and the components of the LVS model....87

Figure 3.6: Engine Firewall design options (product configurations) 89

Figure 3.7: Dataset in the simulation environment (fuselage, engines and nacelles not shown) - Courtesy of Dassault Systemes, **3D**EXPERIENCE 2017x....90

Figure 4.1: Design-Build-Test cycle. Adapted from (Wheelwright & Clark, 1992) 95

Figure 4.2: Denso’s R&D Process. Adapted from (Ward et al., 1995)....96

Figure 4.3: Three core qualities of a prototype. Adapted from (Houde & Hill, 1997) 100

Figure 4.4: Experimental builds during the development of a complex aerospace system 102

Figure 4.5: From component-focused CAD/CAE/CAM to system-focused virtual prototyping. Extended from (Ryan, 1999) 104

Figure 4.6: Combining physical test and simulation to deliver innovation. Adapted from (Van Der Auweraer & Leuridan, 2005) 106

Figure 4.7: Experimentation as a four-step iterative cycle. Adapted from (Thomke, 2008) 108

Figure 4.8: Experimental builds during the development of a complex aerospace system (detailed view)....111

Figure 4.9: Three dimensions of DMU support. Adapted from (Dolezal, 2008)....113

Figure 4.10: Level-by-level vs. non-isomorphic hierarchies models. Adapted from (Van Den Hamer & Lepoeter, 1996) 114

Figure 4.11: Requirements for Product Structure and Bill of Materials progression 117

Figure 4.12: Relationship between geometry, product structure data and metadata on a simplified example 119

Figure 4.13: Complementary and configurable information structures - a diagrammatic analysis 124

Figure 4.14: "As-designed" forward engine mount structure and corresponding 3D representation 127

Figure 4.15: A design arrangement of the forward engine mount components...........................128

Figure 4.16: Development & Testing complementary structure of the forward engine mount (schema) 130

Figure 4.17: Development & Testing complementary structure of the forward engine mount (simulation). Courtesy of Parametric Technologies Corp..131

Figure 4.18: An industrial large-scale deployment of *as-tested* structure. Courtesy of Dassault Systemes, **3D**EXPERIENCE 2014x 135

Figure 4.19: Tag cloud from the PLM transformation structured focus group data collection ...137

Figure 5.1: Simplified configuration methodology to represent sets and physical prototypes (manufacturing process not represented) 140

Figure 5.2: Adopted multi-domain product modelling framework (no variability represented) .147

Figure 5.3: Example of multi-domain representations for the development, testing and service of a turbojet (no process view, no variability represented) 148

Figure 5.4: Domain view of the E-FM tree model (no variability represented) 150

Figure 5.5: Adopted multi-domain product modelling (no variability represented)....................152

Figure 5.6: CCS conceptual entity relationship diagram 155

Figure 5.7: Illustration of CCS cross-domain implementation (Technological to Physical. No manufacturing process represented)...158

Figure 5.8: Multi-disciplinary virtual assessment of a design alternative...................................162

Figure 5.9: The Learning Value Streams (LVS) model 163
Figure 5.10: PLM Knowledge-Based environment 166
Figure 6.1: An aircraft engine firewall design 171
Figure 6.2: A firewall design with systems interface 172
Figure 6.3: Straight firewall concept 173
Figure 6.4: Deflected firewall concept 174
Figure 6.5: Slope firewall concept 175
Figure 6.6: Legacy dataset for the simulation 181
Figure 6.7: Explicit structure within the technological domain 183
Figure 6.8: Product configuration filtered within the technological domain 184
Figure 6.9: GBOM catalog for a logical feature 186
Figure 6.10: Explicit structure within the physical domain (BOM/DMU) 187
Figure 6.11: Explicit structure filtered within the physical domain (DMU) 188
Figure 6.12: Manufacturing process options for a product configuration (as-designed) 188
Figure 6.13: Virtual simulation of fire extinguishing agent discharge for multiple concepts 189
Figure 6.14: Virtual simulation of accessibility and maintainability for multiple concepts 191
Figure 6.15: Concep#2 FIREX agent volumetric concentration vs. elapsed time (by ISA altitude) 192
Figure 6.16: Optimal firewall concept converged from the design bandwidth 193
Figure 6.17: Instantiation in the existential domain - Build serial 194
Figure 6.18: Improved firewall driven by explorations of the design bandwidth 197
Figure 7.1: CCS effectivity-based variability and change evolution coverage 203
Figure 7.2: A model for practical implementations of LPD in large-scale industrial contexts....205

LIST OF SYMBOLS AND ABBREVIATIONS

3D	Three dimensions
AO	Architectural option
BOM	Bill of materials
CAD	Computer aided design
CAE	Computer aided engineering
CAM	Computer aided manufacturing
CCS	Configurable complementary structures
CE	Concurrent engineering
CM	Configuration management
dBOM	Development BOM
DMU	Digital mock-up
DP/**dp**	Design parameter/relationship
DRM	Design research methodology
eBOM	Engineering BOM
E-FM	Enhanced function means
Eff.	Effectivity
eq	Equivalence relationship
ETO	Engineer-to-order
fc	Functional coupling relationship
FDMU	Functional DMU
gbom	Generic bills-of-materials relationship
GPS	Generic product structuring
ic	Interface control relationship

IPT	Integrated product team
JIT	Just in time
LF/**lf**	Logical feature/relationship
LPD/LPPD	Lean product development/Lean product and process development
LVS	Learning value streams
mBOM	Manufacturing BOM
MPM	Manufacturing process management
PC	Product configuration
PDM	Product data management
PLM	Product lifecycle management
PD	Product development
PDP	Product development process
PLM	Product lifecycle management
RS/**rs**	Requirement specification/relationship
sb	Satisfied by relationship
SBCE	Set-based concurrent engineering
SBD	Set-based design
SI/**si**	Serialized Instance/relationship
STEP	Standard for the exchange of product model data
TPDS	Toyota Product Development System
TPS	Toyota Production System
uBOM	Unit BOM
xs	Existence relationship

CHAPTER 1 INTRODUCTION

This chapter provides an overview of the thesis work in terms of scope, scientific and industrial goals, the selected research methodology as well as a summary of contributions to the advancement of knowledge and practice in the fields of set-based design and lean product development as they pertain to the aerospace industry. Details about the organisation of the research work are also discussed and the resulting thesis structure is presented in relation to the selected design research methodology.

1.1 Background and research motivation

Design can be regarded as a set of mental and bodily activities that bring human imagination into realities to fulfil some expressed needs. Design and Product Development (PD) may be performed by an individual or by a team. For example, craftsmanship illustrates the individual design/development process whereby production is limited to a unique physical item. Design and development processes in large-scale enterprises conversely entail the dynamics of social organisation (Bucciarelli, 1994) and *shared memory* (Konda, Monarch, Sargent, & Subrahmanian, 1992) in order to produce a full range of customer desired artefacts and services in both consistent and reproducible ways.

In a market driven by increasing customer demands, the focus of manufacturing companies was until recently placed on productivity, quality and supply chains: the motto was to manufacture just in time with reduced effort and cost and to deliver quality goods that meet customer's needs and the company's objectives to the largest extent. This has been extended to the need to bring these products to the market faster, more cost effectively than the competition and with more flexibility and agility in meeting the customer's needs (Clark & Fujimoto, 1991; Reinertsen & Smith, 1991; Thomke & Reinertsen, 1998; Ulrich & Eppinger, 2012; Wheelwright & Clark, 1992; Womack, 2006; Womack & Jones, 1996). Performance and costs related to the production, service and end-of-life stages of a product lifecycle are important fields of improvements, but the critical effect of the design and development processes on those subsequent stages has been recognized. A significant fraction of the product cost, its quality and reliability are determined by the product development stage and the ability of the product to meet its life requirements, and therefore yield effective satisfaction, almost completely depends on the design methodology (Pahl & Beitz, 2013; Suh, 2001; Ullman, 2009). In this context, product design and development is seen as a major competitive advantage enabler and both Industry and Research communities are looking for ways to improve the activity and the related processes (Clarkson, 2006; Wynn, 2007). For instance, Lean thinking applied to product development, often called Lean Product Development (LPD), has received positive and steadily increasing attention during the last decades as a mean to revolutionize and improve Product Development (PD) (León & Farris, 2011). Originally witnessed at Toyota and labelled the Toyota Product Development System (TPDS) (Morgan & Liker, 2006), the system has evolved, from adapting the more mature theories and principles of lean manufacturing to the realm of engineering, to then become theorized on its own. The theory includes inner principles and lean thinking concepts applied to PD such as Waste (Oehmen & Rebentisch, 2010), Value/Knowledge focus (Browning, 2000; Ward & Sobek, 2014) and flow (Beauregard, Bhuiyan, & Thomson, 2014; Browning, 2000; Oppenheim, 2004; Reinertsen, 2007). LPD has furthermore been described with its enablers which allowed for the construction of several models and frameworks suitable for Lean Product and Process Development (LPPD) practical implementation, theory-building and continuous scientific research (Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011; Kennedy, 2003; Khan et al., 2013; León & Farris, 2011; Morgan & Liker, 2006; Ward & Sobek, 2014). For instance, Set-based engineering, set-based design or Set-Based Concurrent Engineering (SBCE, the practice of set-based design) has emerged as a major and key enabler of LPPD. Indeed, SBCE is a field of fertile research activity with the purpose of either solely leveraging its principles based upon the claimed efficiency of the design methodology e.g. (Raudberget, 2015) or/and integrating it into a framework for implementing LPPD as whole e.g. (Khan, 2012).

However, recent studies on lean PD in aerospace industry showed that the maturity of LPD implementation in the industry is low, no more than at introductory level and it has not been possible so far to find a company that coherently combines the LPD enablers into a whole to improve its PD process in a lean way (Al-Ashaab et al., 2016; Beauregard et al., 2014; McManus, Haggerty, & Murman, 2005; Rebentisch, 2008). It is observed that LPD research has focused on the principles and concepts underlying LPD i.e. what should be done, the tools and techniques to implement the approach, rather than converging to a mature theory/model (conceptual focus and theory-building) and the methodologies for the implementation, tool integration, coordination strategies, performance measures and causality effect assessments (Hoppmann et al., 2011; León & Farris, 2011). It is also recommended that the models and methodologies should show compatibility with conventional PD assets and deployed technology in order to avoid disruption but rather stay within the bandwidth of long-term investments while positively balancing the burden of their implementation (Khan, 2012; León & Farris, 2011).

In more details, and as it pertains to the core of this thesis, an evidence-based systematic review of set-based design from 1987 to 2017 showed that:

- Research is required to extend the application of SBCE theories and principles beyond the conceptual design stage, especially implications for detailed design, prototyping, testing and the rest of the product lifecycle;
- There is a lack of holistic model that can support the cross-domain communication, overlapping, narrowing, and refinement of sets and, furthermore, enable the iterative institutional learning capability which is core to SBCE and lean PD;
- Product structuring, configurability and variability are recognized as practical SBCE enablers but they remain scarce within the SBCE literature. Their ability to enable SBCE is not explored from a holistic PD, lifecycle perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework i.e. PDM/PLM;
- Although the literature regularly stipulates that extensive prototyping and testing is key to SBCE in order to foster the Knowledge-Based environment, institutional learning capability and to inform the decision-making process, prototyping (virtual and physical) and testing (incl. simulations) frameworks and activities are rarely addressed within the SBCE literature;
- The effects of major SBCE enablers e.g. product structuring, configurability, prototyping, set-based selection process etc. on the development process performance are rarely studied, whether by experimenting alternative hypothesis or disproving null hypothesis.

It should be noted that capabilities in platform design and variability (modularity and scalability) are acknowledged to intrinsically facilitate SBCE (Johannesson, Landahl, Levandowski, & Raudberget, 2017; Levandowski, Raudberget, & Johannesson, 2014b; Schafer & Sorensen, 2010) because variability within a product architecture makes it practicable to switch between design alternatives. As such, the potential readiness in industry to transition to SBCE and LPD depends on the ability to modularize aircraft functionalities as well as the availability of proper product modelling approaches and methodologies that are compatible with large-scale industry practices.

The main objective of the research is therefore to identify and develop the most essential SBCE-related ingredients of the aerospace industrial product development framework in order to form a holistic model that can support practical implementations of SBCE and LPD from a product lifecycle perspective. This objective can be met by answering the following questions:

RQ1. What aspects, characteristics and features of the aerospace industrial product development are catalysts of a potential transition to SBCE and LPD?

RQ2. What is an appropriate approach for various domains of expertise within the aerospace industrial product development to exchange on the basis of alternative design solutions and furthermore, narrow down to an optimal design by following a set-based convergence process?

RQ3. Does a holistic model exist or can it be developed to support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective?

From practitioners standpoint, the approach to lean in this thesis is geared towards improving multi-domain cross-collaboration by reducing scatter, hanf-offs through streamlined lifecycle management processes i.e. improved flow. More specifically, the proposed model should support generating and securing structured knowledge that entails operational value in large-scale industrial contexts, this by fostering institutional learning capabilities through set-based design explorations of product platforms. As observed by Ward and Sobek (2014), such approach to lean development focuses on creating *(re)usable knowledge* that contribute to consistently profitable value streams and competitive superiority through learning.

1.2 Thesis structure

The research is designed to appropriately answer the type of inquiries by substantiating and validating hypotheses while refuting selected null hypothesis. To summarize, based upon the research objectives, inquiries and the involvement of the author in a community seeking for change towards lean product lifecycle management, the research is designed as a mixed quantitative-qualitative participatory action research by using socio-dynamics data collection/analysis methods from ethnomethodology and an overarching methodology (DRM) by Blessing and Chakrabarti (2009). This overarching methodological sequence is primarily used for planning and executing the design research project while ensuring that focus is placed on achieving substantial progress with regards to understanding and implementation of SBCE and LPD as Design practices.

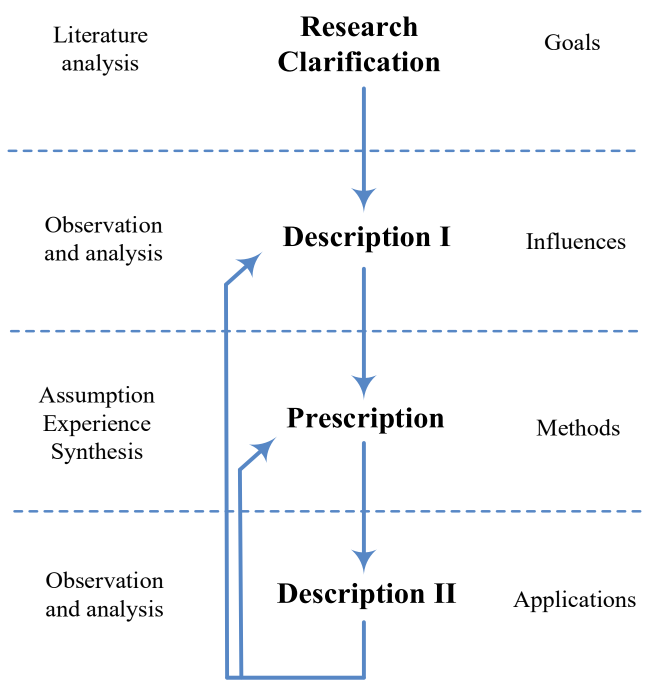


Figure 1.1: Design research methodology. Adapted from (Blessing & Chakrabarti, 2009)

The chapters of the thesis are organised and ordered in a sequence for applying a design research methodology (DRM) through the investigation and construction of the intended holistic model.

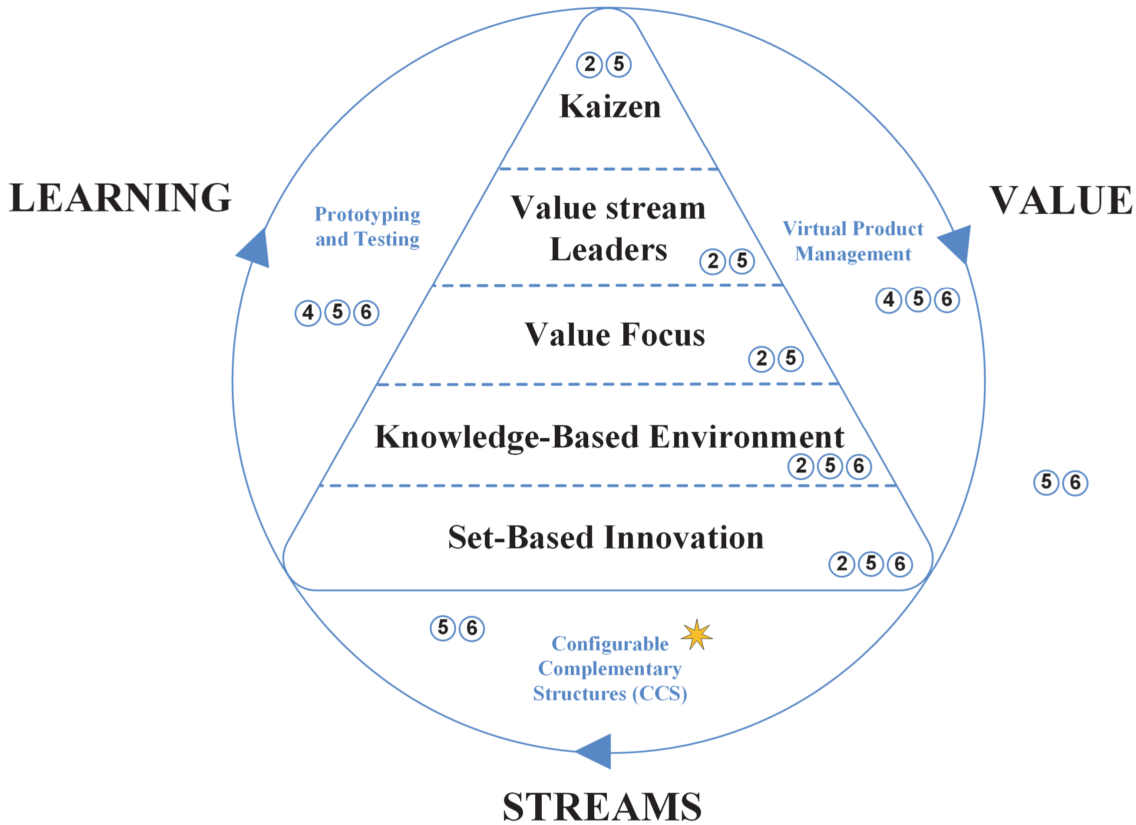


Figure 1.2: Correlation between the thesis chapters and the components of the proposed model

The numbers as shown in above exhibit of the LVS model are thesis chapters and the following table shows the relationship between the thesis chapters and DRM stages.

Table 1.1: Thesis chapters in relation to the design research methodology (DRM)

Thesis Chapter	Chapter Title	**DRM**	Chapter Description
1	Introduction		Research background, motivation, main objective, thesis structure.
2	Literature review	**Research clarification**	Comprehensive literature review of lean thinking and lean product and process development.
			Evidence-based systematic literature review of SBCE (1987-2017). Synthesis Research opportunities.
3	Methodology		Research objectives, questions, hypotheses and criteria. Research paradigm and methodology. Research validation.

Table 1.1 (Cont.): Thesis chapters in relation to the design research methodology (DRM)

Thesis Chapter	Chapter Title	**DRM**	Chapter Description
4	Design prototyping and the digital product information	**Descriptive study I**	Comprehensive study of design prototyping and digital product information theory and practice. Synthesis of gaps and proposal of a methodology to support collaboration during prototyping and testing in a PLM perspective. Research-based case study (Pilot simulation I). Experiences in industry
5	Construction of the Learning Value Streams (LVS) model	**Prescriptive study**	Construction of the Configurable Complementary Structure (CCS) model towards SBCE. Extrapolation to the Learning Value Streams (LVS) model.
6	Product structuring pilot simulation	**Descriptive study II**	Simulation of the proposed product structuring methodology by leveraging a commercially available PLM platform (Pilot simulation II).
7	Conclusions and recommendations		Summary of the findings, contributions, applications and recommendations for future research.

As the research project is driven by considerations into developing scientific knowledge and practice of set-based design and lean product and process development, the success criterion is therefore based on the practicability of the proposed model and methods in industry as well as the contribution to academic research.

This thesis work provides substantial contribution to understanding of LPD and SBCE and furthermore, entails valuable proposal for the practice in industry through the CCS model and the construction of the Learning Value Streams (LVS) model.

CHAPTER 2 LITERATURE REVIEW

A Comprehensive literature review of lean thinking and lean product and process development is performed in the first part of this chapter in order to provide the main research background as well as the theoretical grounds from which SBCE has evolved. The second part of the chapter consists in a systematic literature review of SBCE from 1987, the year in which publications on the Japanese product development practices began to appear, to 2017 which represents the end of the data collection for the literature review pertaining to this thesis. The SBCE systematic literature review is drawn from (NHS, 2001; Nissen, 1996; Tranfield, Denyer, & Smart, 2003) evidence-based systematic review procedure which is applied in this thesis using methods similar to (León & Farris, 2011) and (Baines, Lightfoot, Williams, & Greenough, 2006) in their reviews of lean product development body of knowledge. The third part of the chapter provides a synthesis of the SBCE literature relevant to this research and concludes with research opportunities. Figure 2.1 below illustrates the review approach.

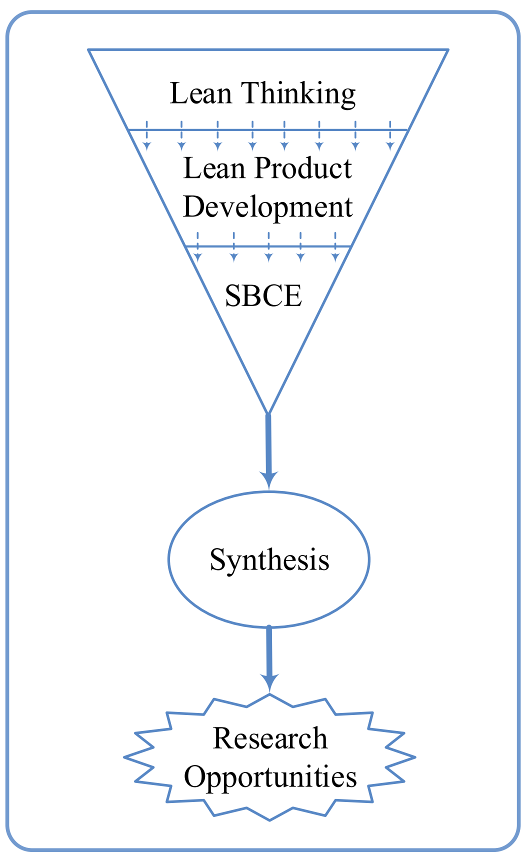


Figure 2.1: Literature review approach

2.1 Genealogy of Lean Product and Process Development

Lean Product and Process Development (LPPD) is reviewed in this section, starting from the evolution of the Lean Production theory to the transition to Lean Product Development (LPD), a theory and practice on its own as well as a major cornerstone in lean thinking.

2.1.1 From Lean Production to Lean Product Development

Lean production in Operations Management research is regarded as one of the most influential manufacturing paradigms of recent times (Holweg, 2007; Schonberger, 2007). Lean Production is consistently associated with the Japanese automakers and especially Toyota with the Just-in-Time (JIT) manufacturing and the Toyota Production System (TPS), which are recognized as significant shifts from the traditional high-volume, highly productive and repetitive manufacturing systems. Lean Production is colloquially known as the first Toyota paradox (Ward, Liker, Cristiano, & Sobek, 1995) and it has been the subject of extensive research until beginning of the 21st century.

Western manufacturers started to pay attention to JIT and TPS following the second oil crisis (1980), which displayed the competitive advantage of the Japanese automakers with increased imports that slowly surpassed domestic sales. The context was then the onset of new explorations for tangible means that could first comparatively demonstrate an automaker superiority in manufacturing performance, second, explain the settings and reasons behind the system superiority and finally, third, evaluate the gap in the superiority. The International Motor Vehicle Program (IMVP) existed at MIT by that time with research activities centered upon the future of the automobile. The program then evolved through the 80's to meet the purpose of describing and assessing the gap between the Japanese and Western automakers using a common reference assembly plant benchmarking methodology the researchers may develop. Indeed, Womack and Jones designed the benchmarking methodology and tested it at Renault's facility in Flins, France in 1986 (Womack, Jones, & Roos, 1991). Initial productivity and quality metrics were set by John Krafcik, who, as the first American engineer to be hired by NUMMI, was able to collect data both from Toyota's Takaoka plant in Japan, during his training to join NUMMI, and also from GM Fremont plant before it became NUMMI. Krafcik then joined the IMVP program as an MBA student and went with Womack in 1986 to formally start the assembly plant study by visiting GM's assembly plant in Framingham, Massachusetts (Holweg, 2007). Data from Flins, Framingham, NUMMI and Takaoka plants formed the basis of the first international assembly plant benchmark which was reported in Krafcik paper "Learning from NUMMI" (Krafcik, 1986). As the impact of the study encouraged more funding and improvement of the benchmarking methodology, more researchers joined the program including John Paul MacDuffie who, with Krafcik, will both take responsibility between 1986 and 1989 to complete the benchmarking study of 70 assembly plants around the world. The larger scale study and data then became the foundation of dissertations, notable papers and ultimately the book "*The machine that changed the world*" (Krafcik, 1988; MacDuffie & Krafcik, 1992; Womack et al., 1991).

Table 2.1: Production system characteristics (Krafcik, 1988)

	Craftsmen	Pure Fordism	Recent Fordism	TPS
Work Standardization	Low	High, by managers	High, by managers	High, by teams
Span of Control	Wide	Narrow	Narrow	Moderate
Inventories	Large	Moderate	Large	Small
Buffers	Large	Small	Large	Small
Repair Areas	Integral	Small	Large	Very small
Team Work	Moderate	Low	Low	High

The results and observations these authors made were striking. First because they exhibited how Honda, Toyota and other Japanese automakers were leading a revolution in Manufacturing by developing and building high quality cars in less time, less space and with far less resources than their U.S. and European competitors. Secondly, because by using the performance results of the Japanese transplants in the U.S., these authors evidenced that lean practices were fully transferable in every country and every organisation.

"*The machine that changed the world*" provided a fresh new perspective on the Toyota way by encompassing every aspect of a manufacturing company in the term "*lean production"*, not just the actual production phase. It should be noted that the term lean production was previously coined by Krafcik (1988) to describe the Japanese production system whereby the use of less effort, space and material resulted into higher output and quality. Womack, Jones and Roos, in "*The machine that changed the world*", emphasized the fact that TPS was the operations portion of the total management system at Toyota and that it was tied and remarkably consistent with the main other subsets of the system, namely, the Toyota Product Development System (TPDS), Toyota's supply chain integration process and its customer management process (Womack et al., 1991). The "*Machine*" extended lean manufacturing and TPS (known until then for the methods for waste and resources reduction in manufacturing) to include a broader definition of a "*lean enterprise".* Although the main focus of the book was on manufacturing processes, Womack, Jones and Roos discussed Lean Product Development (LPD) through the TPDS by observing that the process was as much as important as lean manufacturing in contributing to the success of Toyota's total management system. The authors described techniques Toyota used in their TPDS including a strong project leadership with direct control over functional resources and project deliverables, teamwork, early and standardized communication, and simultaneous development. When looking at Product Development (PD) strategies that evolved through time and which became the main subjects of research and practice across industry, independently of the Lean thrust, one can argue that the last three TPDS techniques described above are mere components of Concurrent Engineering (CE). CE similarly reduces uncertainty by exchanging preliminary information earlier and, reduces time-to-market and the overall cost and effort of a PD process by carefully overlapping the development activities (Clark & Fujimoto, 1991; Loch & Terwiesch, 1998; Prasad, 1996; Terwiesch & Loch, 1999; Terwiesch, Loch, & Meyer, 2002). However, what makes LPD fundamentally different from CE, as initially described in the "*Machine*" with TPDS, is the identification of "Value", the elimination of "Waste", the improvement of the flow of "Value", the distinctive management strategies and an enterprise-wide common philosophy that is implemented across all business processes using the same format and basic principles (Haque & James-moore, 2004). As a result, CE and LPD are complementary approaches which simply do not act at the same level or on the same concepts within the PD process.

Following the "*The Machine*", Womack and Jones encapsulated Lean Thinking into five lean principles described as: (1) defining or specifying the value from the customer standpoint; (2) identifying the value stream and eliminating waste; (3) removing hindrances to value flow; (4) enabling customer to pull the (value) process and finally; (5) promoting continuous improvement i.e. waste removal in the search for perfection (Womack & Jones, 1996). In other words, lean would become a system that can be achieved by reducing, eliminating waste and non-required actions, linking all steps in the process that create value in an unbroken sequence, embedding built-in automation that signals broken streams and promoting learning through waste elimination and value creation cycles (Haque & James-moore, 2004; Spear & Bowen, 1999). Womack and Jones's lean principles, Liker's fourteen principles to lean (Liker, 2004) and some key implementation guidelines that include Process Kaizen and Flow Kaizen by using Value-Stream Mapping (VSM) (Rother & Shook, 2003) have been widely adopted by numerous manufacturing organisations across the world to make lean a reality of their strategic and day-to-day manufacturing operations. As lean became widely used in manufacturing and its positive impact confirmed, the interests grew in what lean principles would mean for other areas especially Engineering and PD and how they can be applied. Similarly, niche industries like aerospace, which was originally reluctant to implement lean manufacturing, showed interest in how lean can be implemented in their specific context. The Lean Aerospace Initiative (LAI, now Lean Advancement Initiative) was created for instance at MIT by gathering a consortium of aerospace industries to conduct research following the IMVP model. Lean principles were then adapted and widely applied to both civil and military aerospace manufacturing operations (Murman et al., 2002). Nevertheless, LPD and TPDS remained less understood, the translation of the lean principles from manufacturing operations to engineering were lacking and models to transpose key lean concepts such as value, waste, flow, etc. in support to and improvement of engineering PD activities were also missing.

The examples discussed and the evolution of lean show that lean may have originated from grasping the Japanese and Toyota ways but it cannot be confined to principles, methods and philosophies driven from there. The recent 2009 crisis Toyota faced with the quality of its product, or some may say, the perceived quality of its product, somehow ironically resonates with 'fragile' which is how the IMVP researchers used to call lean before it was changed to a more positive connotation (Holweg, 2007). However, Toyota model remains praised in the literature and industry as the reference model embodying the *lean enterprise* philosophy and concepts. For instance, as Toyota passed GM in 2006 to become the world's largest automaker, Womack published a paper in the Mechanical Engineer confirming the superiority of the *lean enterprise* as predicted by the "*Machine*" (Womack, 2006). Although the predicted time was delayed fifteen years later, Womack emphasizes that the timeline is not the matter of importance but rather the components of the *lean enterprise* as witnessed with the Japanese automakers back in the 90's. The five key elements of the lean enterprise are recalled i.e. an unusual product development process, an integrated supplier management process, a focused customer management process, an overarching enterprise management process and a streamlined production process from order to fulfillment. Each process is believed to be superior to the process employed by mass producers for the same tasks. Lean product development is advocated to allow a company to produce vehicles in less development time, using less hours of engineering and producing fewer defects while investing less capital and meeting a broad range of customer's needs. The key enablers of this product development process are the chief engineer concept, the concurrent set-based design and the high-speed prototyping using trade-off curves to avoid searching and inventing solutions that were already documented. Womack uses the example of the Toyota Prius model to demonstrate the predicted impact of the lean product development process. For the Prius, Toyota was able to hear the voice of the customers about hybrids very early and then was able to quickly integrate several new technologies into a vehicle that reported as the most reliable car sold in the US according to Consumer Reports (Womack, 2006). Womack concludes by urging the mass producers like GM and Ford to introduce all the elements of the *lean enterprise* in their system in order to resolve the crisis they face.

2.1.2 Origins of Lean Product Development and evolution

Product Development is first defined in this section and models for representing and organising the product development process are described. Contemporary definitions of lean product development are then outlined and the origins and evolution of lean product development are finally presented. It should be noted that New Product Development (NPD) and New Product Introduction (NPI) are equivalent terms to refer to PD i.e. Product Development. Similarly, Lean Product Introduction (LPI) is a term that refers to LPD i.e. Lean Product Development (Haque & James-moore, 2004). PD and LPD are used in this dissertation to refer to the related concepts and the equivalent terms.

2.1.2.1 Product Development in the literature and industry

Product Development (PD) is defined as a network of interrelated activities, including decision-making events, that transform a market opportunity into a product that meets the end user needs as well as the strategic goals of a company (Browning & Ramasesh, 2007; Krishnan & Ulrich, 2001). From an implementation standpoint, PD can be regarded as the overlapping sequence of design, engineering, prototyping, testing and manufacturing processes involved from the definition of the market needs to the end of the production ramp-up (the point in time when the satisfactory manufacturability of the product is reached) (Fortin & Huet, 2007; Terwiesch et al., 2002; Ulrich & Eppinger, 2012). At a high level, few PD process models have been used in industry (Browning & Ramasesh, 2007). These include:

- The basic stage-gate process or waterfall model which is composed of a sequence and preferably overlapping activities and the reviews used to grant full access to the next phase (Cooper, 1994);
- The spiral model which reduces risk and uncertainty through a planned set of interactions, iterations and reviews that result into convergence and consensus (Boehm & Hansen, 2000; Evans, 1959);
- The systems engineering "V" model[1] in which the design problem is decomposed into requirements followed by the definition (design) and then verification and validation (Forsberg & Mooz, 1999).

---

[1] The "V" proceeds from the high level, less tangible requirements, to the low level discrete solutions (design) for the decomposition and definition (left side of the V), then integrates from the bottom to the top through the verification (right side of the V). The steps in the branches are validated against each other at every level moving vertically inside de "V".

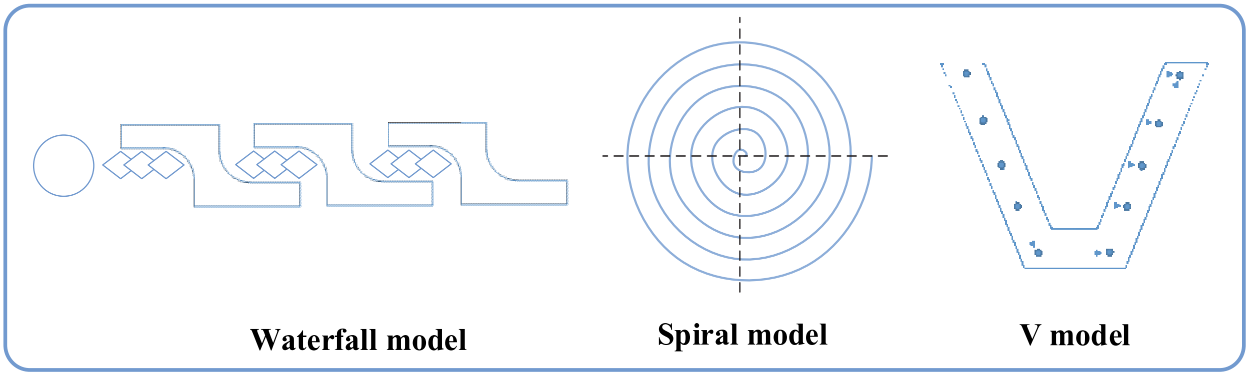


Figure 2.2: Three models of product development

Sometimes regarded as distinct models of product development, many approaches and frameworks can be found in the literature and industry including the incremental, agile development and scrum which are nowadays getting increasingly positive attention. These approaches are usually performed following one of the main three models described above. For example, the so-called incremental build model in software development combines the waterfall model with an iterative approach to prototyping (Larman & Basili, 2003). Agile development is product focused rather than project focused. It iteratively matures the product through rapid prototyping, concentrating on subset requirements and the resulting product performance and user experience that incrementally drive to the target final product (Boehm & Turner, 2004). Agile development can be seen as an iterative and incremental process in which design, prototyping and testing happens together in a same phase as opposed to a development process phased by each discipline activity and deliverables. There is also more flexibility with the product approximation and documentation in agile development, which raises concerns about the potential chaos from missing appropriate documentation by the end of the process (Boehm & Turner, 2004). Not going by a strict plan and not being able to assess the conformity of both the product and the process by the usual means may also be perceived as shortfalls. Likewise, scrum focuses on self-organised, co-located participants that collaborate closely through iterative and incremental development cycles which, in contrast to agile development, are very short. These short concurrent engineering development cycles are called “sprints”. They are supported by evidence-based and empirical approaches, acknowledging the fact that it is not possible to capture what the customer wants with exactitude (Schwaber, 1997). Each cycle rather focuses on quickly delivering what appears to be enough so far. A sprint usually results into operational prototypes (also found in the spiral development process) which are then followed by benchmarks that become the basis for the next sprint. The *minimum viable product* of the lean startup methodology (Lenarduzzi & Taibi, 2016) can be regarded as a tuned operational prototype undergoing a spiral or scrum development process. As market volatility, high variability in customer demands and time-to-market become critical factors for competiveness in industry, agility is sometimes perceived from an operational standpoint with regards to the ability of a company to quickly and effectively respond to changing markets (Kidd, 1996). From that viewpoint, agility may be accomplished through the synergistic combination of robustness, resilience, responsiveness, flexibility, innovation and adaptation within the context of interest (Alberts & Hayes, 2003). For instance, Lemieux, Pellerin and Lamouri (2013) combined this agility framework with lean principles to propose a balanced leagile product development methodology in the fashion industry. In all forms, the incorporation of agility in PD processes has been advocated to increase *development flexibility* (Thomke & Reinertsen, 1998). These authors state that it can be achieved by:

1. Adopting flexible technologies:
    - Find technologies that allow for fast and low cost design iterations.
2. Modifying management processes:
    - Progressively lock-down requirements;
    - Keep multiple back-up approaches viable even after concept selection;
    - Provide a sound framework for making trade-off decisions;
    - Measure and improve reaction time;
    - Make piecewise commitments versus binary choices;
    - Carefully structure design tasks.
3. Leveraging design architecture:
    - Use modular product structures;
    - Isolate volatility in the design;

- Reduce coupling between modules.

As it will later be discussed, these agile PD guiding principles fairly resonate with set-based thinking principles and practices when combined with modularity and product platform design.

In parallel to above industrial generic PD process models, researchers may sometimes look at PD by means of design strategies, the form by which the process is described in the literature and the methods and mediums used by practitioners to meet the purpose. The research objective is usually about finding new approaches to improve product development as a generic process. Wynn in his doctoral dissertation discusses models of product development by contrasting views, dimensions and proceedings of the PD process, as available from the literature, in order to combine them into a framework for organising models of design and development. Wynn's framework synthesizes below PD models in order to characterise various PD processes and subsequently improve them according to the typology (Wynn, 2007):

- Stage vs. activity based models: Serial, cyclic, repetitive or solution space concentric. The model addresses the morphological and problem-solving dimensions. The stage-gate process is an example of solution space concentric model;

- Solution vs. problem oriented strategies: Depends on whether the emphasis is placed upon a solution which is then analysed and refined or whether the focus is initially on the problem, abstracting and decomposing it before generating a range of possible solutions. This can be thought as abductive reasoning vs. inductive/deductive reasoning in design (Cross, 1989). Point-based design and set-based design which will later be analysed in this review are classification examples readily perceptible by the solution vs. problem model;

- Abstract vs. procedural vs. analytical approaches: Depends on whether the approach is described using high level abstraction or rather concrete in nature focusing on specific aspects or particular instances of the design process. A design process described for example by the sequence Explore, Generate, Evaluate, Communicate would be considered an abstract model. Procedural approaches can be decomposed into two categories, i.e. descriptive approaches that result from investigating actual design practices and documenting them into texts and, prescriptive approaches which are synthesis of best practices targeted for a specific domain or expertise e.g. Mechanical design, engineers, managers, etc. There is no clear separation between abstract and procedural approaches as observation of design practice can lead to procedurally document the practice into abstract terms. Procedural approaches also include dimensions related to models (form) vs. methods (procedure) on one side and, design-focused (application of models and methods) vs. project-focused (management of a design endeavour) on the other side. Analytical approaches rather involve lower level representations in support to planning, performing detailed activities and guiding decisions. Analytical approaches similarly include two dimensions split into activity-focused, information-focused and actor-focused on one side and, task network models, queuing models, multi-agent models and system dynamics models on the other side.

The exhibit below shows a PD process that can be interpreted combining stage/activity representation, problem oriented strategy and abstract and procedural representations that involve design-focused and project-focused components. Key activities in the scope of the present research are highlighted.

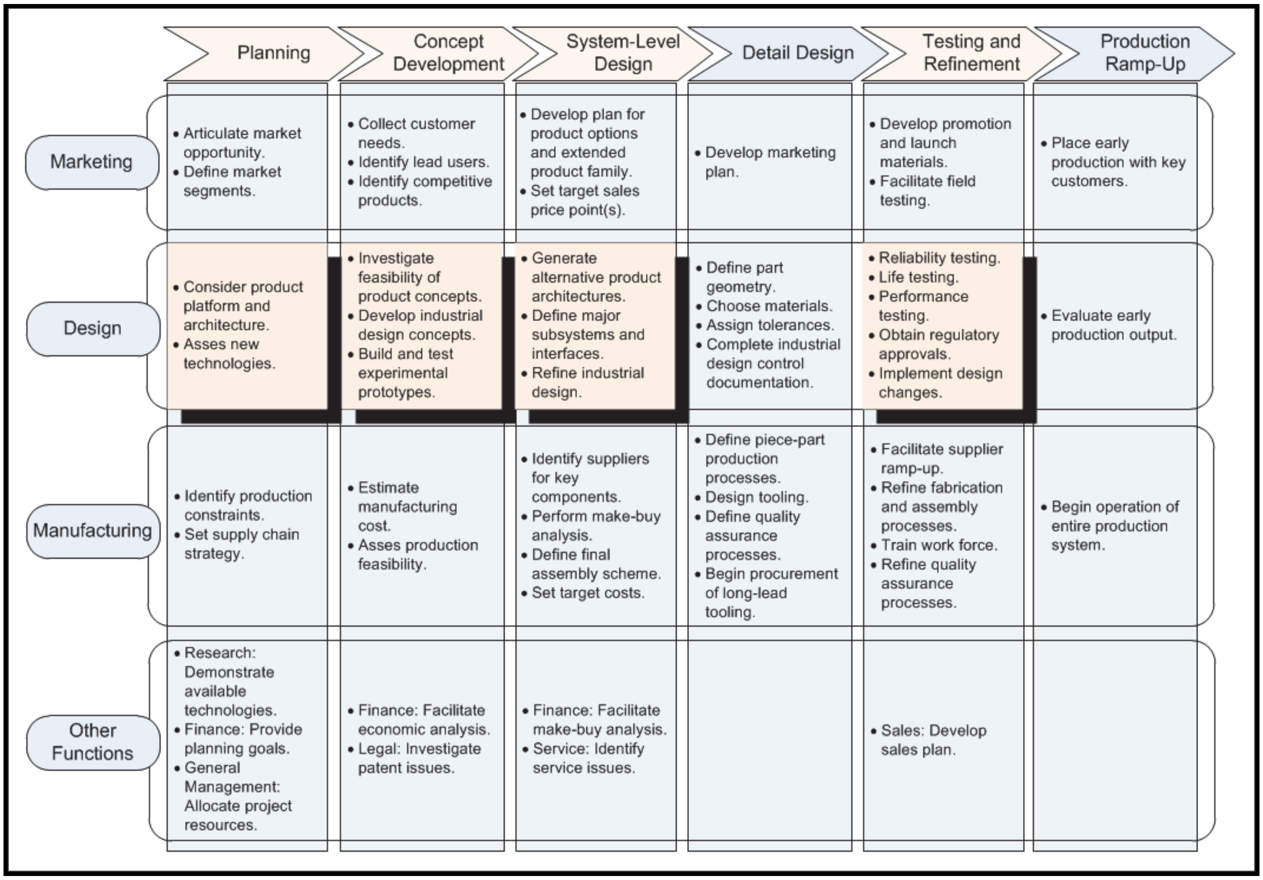


Figure 2.3: Phase-function view of a generic product development process. Adapted from (Ulrich & Eppinger, 2012)

According to Ward and Sobek (2014), the aim of a development activity is to produce operational value streams that run from suppliers through factories, into product features and out to customers. These streams do not exist until development processes create them. CAD geometry, FEA, layouts, product structures, Bills of Material, drawings, assembly plans, test results, manufacturing instructions, etc. have value in the sense that they create operational value streams for the main customer that is Production, and by consequence, the end customer who is entitled to benefit from an impressive product quality. Ward and Sobek (2014) argue that lean development focuses on creating *(re)usable knowledge* that contribute to consistently profitable value streams through learning. More generally, Lean Product Development (LPD) can be viewed as "*the cross-functional design practices (techniques and tools) that are governed by the philosophical underpinnings of lean thinking – value, value stream, flow, pull, and perfection – and can be used (but are not limited) to maximize value and eliminate waste in PD*" (León &

Farris, 2011). The process, as described, can be perceived as abstract rather than any of the procedural, analytical, problem/solution or stage/activity models of Wynn's framework. At the same time, the definition accurately resonates with the lean philosophy and can be regarded as a strategy that involves many other concepts/processes which in turn may better fit into more perceptible models of the previous framework. Set-based design process, as it will shortly be discussed, is for example the product design approach in LPD that can be better classified in terms of problem/solution, abstract/procedural/analytical or stage/activity model.

To summarize, León and Farris definition of LPD, which is synthesized from a systematic literature review of LPD, elevates value and waste as key concepts in LPD. In a nutshell, lean thinking focuses on eliminating knowledge waste in all its forms and creating value through learning (Huet et al., 2009; Ward & Sobek, 2014). For instance, Ward and Sobek (2014) claim that LPD is about creating value in terms of usable knowledge for the operational value streams and, as such, they identify knowledge wastes as the most important wastes in PD. Three main categories of knowledge waste are proposed, each having two additional sub-categories: (1) Scatter (Communication barriers, Poor tools); (2) Hand-off (Useless information, Waiting) and; (3) Wishful thinking (Testing to specifications, Discarded knowledge). Ward and Sobek categories of waste share many similarities with Morgan's (2002) categories when it comes to value stream flow, learning organisation capability and knowledge capture and reusability. Regarding consensus, it has been debated in the literature whether the focus should be upon creating value or eliminating waste in LPD, with the former being preferred (Browning, 2000, 2003). It has furthermore been debated whether lean methods in engineering should prioritize streamlining and accelerating flow rather than eliminating waste per se, with the former being advocated again (Browning, 2000; Hines, Francis, & Found, 2006; Oppenheim, 2004; Reinertsen, 2007). Optimized and faster flow improves interactions in design processes, thereby reducing uncertainty, risk, and ultimately waste. It is commonly agreed that the value of PD can be expressed as a function of information produced on time to minimize wasted efforts and to reduce uncertainty (Beauregard et al., 2014). The right information, in the right amount, available at the right time.

2.1.2.3 Origins and evolution of Lean Product Development

Clark et al. (1987), Womack et al. (1991), Ward et al. (1995) and Sobek & Ward (1996) are arguably the first to recognize that Toyota Product Development System (TPDS) was as much important in Toyota's total management system as lean manufacturing (the first Toyota paradox). These authors stressed the fact that the product development process at Toyota (the second Toyota paradox) was following a fairly unusual paradigm and that it was in fact making Toyota the fastest and most efficient developer of autos (Ward et al., 1995). Some dozen principles of lean product development derived from TPDS are nowadays documented (Morgan & Liker, 2006) and many companies are striving to implement the approach. However, it has become obvious, in theorising LPD, that the philosophy cannot be fueled only by Toyota ways, principles and techniques but should incorporate other improvement approaches that equally support developing and manufacturing products or services faster, with less effort and ultimately with fewer product and process discrepancies (Browning, 2000; Karlsson & Ahlström, 1996; León & Farris, 2011). Basically more value, less waste. In fact, researchers have originally attempted to adapt lean manufacturing principles and the strategies for waste reduction to Product development (Baines et al., 2006). For example, Reinertsen and Smith (1991) adapted the pull concept of JIT to the use of partial information in product development with the purpose of compressing the development time by accelerating the exchange of preliminary small package information as they become available. Haque and James-Moore (2004) applied Womack and Jones's (1996) five lean thinking and lean manufacturing principles (specify value, identify the value and eliminate waste, make the value flow, let the customer pull, pursue perfection) to product development by adapting the principles to the realm of the development process. Oppenheim (2004) similarly developed an approach based upon Womack and Jones's five principles and combined them with aerospace engineering best practices in order to apply lean in aerospace systems engineering. The approach was then extended to include an additional principle from Sugimori et al. (1977) about people valorisation and respect (Oppenheim, Murman, & Secor, 2011). Morgan and Liker (2006) proposed thirteen principles derived from the TPDS to allow the implementation of LPD based upon a people, process and tools and technology triadic framework. To elaborate further on the different trends researchers and practitioners have taken to devise LPD, Khan et al. (2013) studied LPD literature under five categories related to the researcher approach. A first category that includes authors presumably rebranding CE as LPD; A second category of authors adapting ideas from lean manufacturing to PD in combination with other theories; A third category of authors integrating elements of TPDS with lean manufacturing principles and methods to apply them to PD; A fourth category comprised of authors describing Toyota principles and practices based upon observations and experiences with TPDS and finally; A fifth category about authors applying TPDS principles and practices in industry. As a result of the study, Khan et al. (2013) claim that LPD in its current state should refer to a PD theory that is based upon Toyota's PD principles and practices (best reference for lean PD as of now) and not lean manufacturing or any other methodology. Khan et al. (2013) argue that further research is required to progress LPD into a theory in its own and therefore potentially remove constraints to Toyota's practices. Indeed, Khan in his doctoral dissertation (2012) proposes a set of 58 LPD enablers both reused from existing key LPD reviews (Hoppmann et al., 2011; León & Farris, 2011) and extracted from the category 4 of the research work i.e. the category dealing with authors that derive LPD from observations and experiences with TPDS. The research work subsequently converges into a conceptual LPPD model drawn from five main enablers among which Set Based Concurrent Engineering (SBCE) is positioned as the core enabler/process within LPD, with the remaining supporting it: Value Focus (usable knowledge), Knowledge-based environment, continuous improvement and chief engineer. Following industrial assessments of the enablers through structured interviews in five engineering companies, Khan (2012) reports that it was not possible to find a PD model in industry that combines the enablers into a coherent unit. The research work then concludes on the need to demonstrate the applicability of the conceptual LPPD model, assess its impact on PD, and develop the methods and tools that will support LPPD implementation in industry without disrupting the existing severe PD settings, conventional tools and techniques (Khan, 2012; Khan et al., 2013).

As value becomes contrasted with waste reduction in product development and LPD is further isolated from the Japanese benchmarking (Baines et al., 2006; Browning, 2000, 2003; Ward & Sobek, 2014), LPD is thought to include broader improvement strategies, methodologies and techniques that may influence PD value streams in order to reduce time-to-market and minimize the overall cost and effort of a PD process, e.g. Concurrent Engineering (CE) and agile product development (Lemieux et al., 2013; León & Farris, 2011). León and Farris performed a systematic review of LPD research leveraging a new LPD knowledge domain framework that categorises LPD research work based upon the perceived involvement with (1) PD decisions; (2) strategy; (3) supplier/partnership; (4) Knowledge-Based networks; (5) process modelling; (6) PD performance and; (7) lean manufacturing principles. León and Farris findings shows that LPD literature has focused on the principles and concepts underlying LPD i.e. what should be done, and also the tools and techniques to implement the approach, rather than converging to a mature theory (conceptual focus and theory-building) and the methodologies for the implementation, tool integration, coordination strategies and LPD performance measures (León & Farris, 2011). It is also pointed that the models and methodologies should provide new capabilities that positively balance the burden of their implementation in the context of existing PD assets, technology and proven benefits. Major directions for future LPD research, as extracted from León and Farris review and pertaining to the present research work, are listed below (León & Farris, 2011):

- Decision-based:
    - Identification of adequate decision-making approaches that foster coordinated decisions across functions;
    - Alignment mechanisms for strategic and operational decisions and the study of their interactions;
- Strategy:
    - The definition of coordination mechanisms between functions and activities across projects, according to the PD strategy;
- Knowledge-based networks:
    - Triggering factors for tacit-explicit knowledge exchanges;
    - Effective mechanisms to maximize the knowledge creation and minimize the knowledge integrity loss when transferred to other PD contexts (learning network structures, techniques or tools);
- Lean manufacturing-based:

  - Understanding and improving value in PD (e.g. mechanisms for maximising flow and information processing, quality measures for information);
  - Tool adaptation to non-Japanese companies as well as tool integration.

Another contribution to organising LPD research is the work done by Hoppmann. Hoppmann's research work combined a review of LPD literature in the strict sense with techniques for content analysis applied to 27 key publications identified in the first step (Hoppmann, 2009; Hoppmann et al., 2011). The systematic content analysis approach resulted in the synthesis of eleven LPD components that constitute a lean PD system:

- Strong project manager;
- Specialist Career Path;
- Workload Leveling;
- Responsibility-based Planning and Control;
- Cross-project Knowledge Transfer;
- Simultaneous Engineering;
- Supplier Integration;
- Product Variety Management;
- Rapid Prototyping, Simulation and Testing;
- Process Standardization;
- Set-based Engineering.

While Hoppman et al. (2011) also recognize that set-based engineering, Set-Based Design (SBD) or SBCE (the practice of set-based design) is a strong component of a lean PD system, they argue that building a larger number of physical prototypes might be too expensive in the case of complex and costly products, making virtual prototyping techniques more viable options. Hoppman furthermore analyses the relationships between the eleven components of a lean PD system for the sake of better understanding, formalising and structuring the required interaction between the components while studying or implementing the system. Although no meaning was found to 30 of a total of 110 theoretical qualitative interdependencies between the eleven LPD components, the result is unique in its kind and it provides a rich detailed matrix of the existence and hypothetical nature of a relationship between two components of the system (Hoppmann et al., 2011). For example, SBCE is, for the first time, thoroughly examined in relation with the other LPD components resulting in the suggestion that 6 of the LPD components are prerequisites to SBCE: Process standardization, Workload Leveling, Specialist Career Path, Product Variety Management, Rapid Prototyping, Simulation and Testing and Supplier Integration. The other components identified not to be prerequisite are rather interacting with SBCE in various ways and levels in support to its effectiveness (Hoppmann et al., 2011). Hoppman et al. (2011) express the need to fully explore the nature of identified relationships and they suggest a number of research directions to advance understanding and organisation of LPD frameworks. Refocusing LPD components understanding outside the context of TPDS and through more in-depth case studies is regarded as a key direction for future work as well as further empirical research on LPD from a holistic systems and inner interactions perspective.

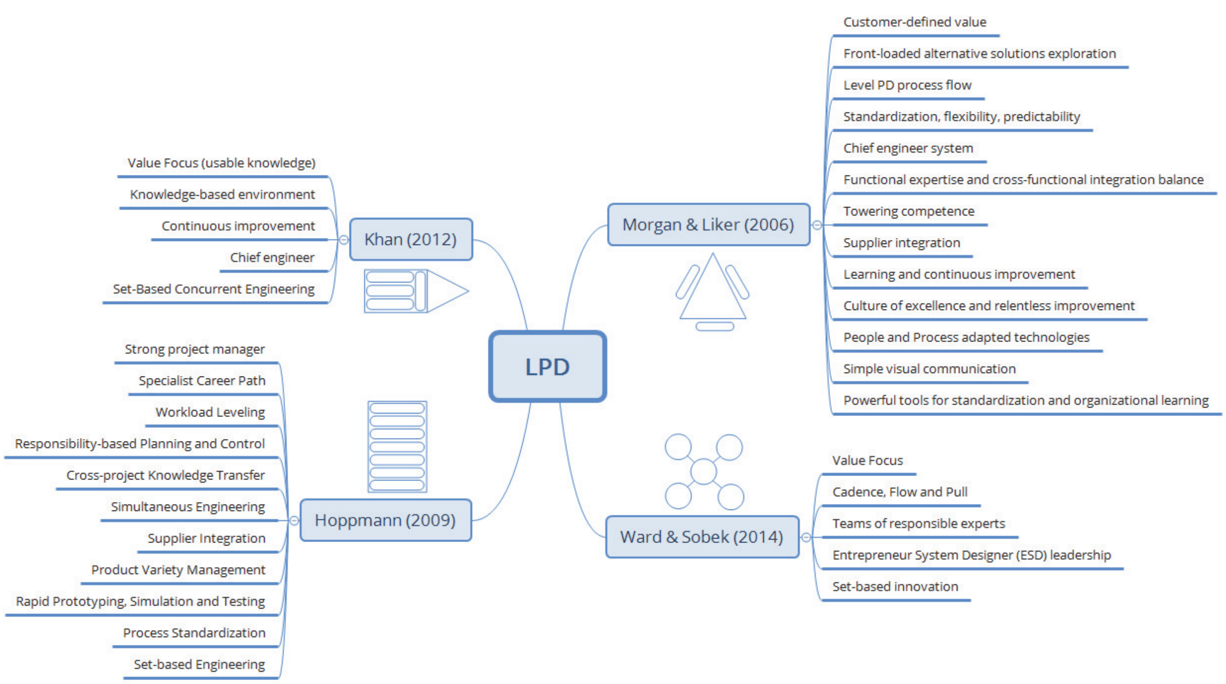


Figure 2.4: Various models of LPD

As previously mentioned, recent studies on lean PD in aerospace industry show that the maturity of lean PD implementation in the industry is low, no more than at introductory level and it has not been possible so far to find a company that coherently combines LPD enablers into a whole to improve its PD process in a lean way (Al-Ashaab et al., 2016; Beauregard et al., 2014; McManus et al., 2005; Rebentisch, 2008). The review of the literature shows that LPD research has focused on the principles and concepts underlying LPD i.e. what should be done, the tools and techniques to implement the approach, rather than converging to a mature theory (conceptual focus and theory-building) and the methodologies for the implementation, tool integration, coordination strategies, performance measures and causality effect assessments (Hoppmann et al., 2011; León & Farris, 2011). It is also pointed that the models and methodologies should show compatibility with conventional PD assets and deployed technology in order to avoid disruption but rather stay within the bandwidth of long-term investments while positively balancing the burden of their implementation (Khan, 2012; León & Farris, 2011). Set-based Engineering, set-based design or SBCE (the practice of set-based design) is recognized as the keystone of lean PD by all authors and they position it as the core enabler of LPD. The next section will discuss SBCE in particular, explore its maturity in the research literature as well as its level of understanding and implementation in industry.

2.2 Set-based Concurrent Engineering (SBCE) in the literature and industry

This section reports on a systematic literature review of SBCE from 1987, the year in which publications on the Japanese product development practices began to appear, to 2017 which represents the end of the data collection for the literature review pertaining to this thesis. The SBCE systematic review is drawn from (NHS, 2001; Nissen, 1996; Tranfield et al., 2003) evidence-based systematic literature review procedure which is applied in this thesis using methods similar to (León & Farris, 2011) and (Baines et al., 2006) review of lean product development body of knowledge. The section is divided in five parts. The first part provides some background about SBCE, the second part presents a newly devised dual framework for the systematic analysis of SBCE, the third part presents the results of the systematic review by means of quantitative analysis and the last two parts qualitatively discuss the content of the findings to conclude with research opportunities.

2.2.1 SBCE Background

According to Clark and Fujimoto (1991), the earliest decisions in product development have the largest impact on the overall quality of the product (effectiveness) and the overall cost of the project (efficiency). Many approaches to engineering design are focussed on reducing cycle time following the famous motto "do it right the first time". In terms of design strategy, this has often been translated into a need to propose the right solution as fast as possible. As observed by Sobek and Ward (1996), when dealing with the development of complex products, many US companies force the engineering teams to propose a feasible concept quickly so that it can then be optimized through numerous iteration loops. This pattern is understood as point-based because it focuses on one solution at a time and progressively refines it until all stakeholders are satisfied with the outcomes. Figure 2.5 illustrates this view.

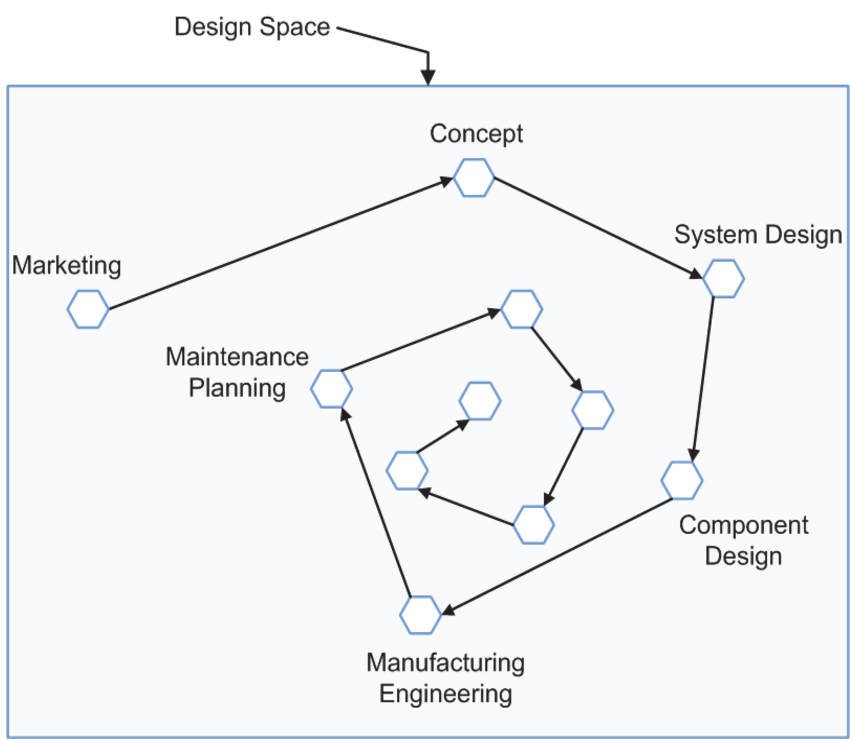


Figure 2.5: Point-based approach to the design of a complex product. Adapted from (Ward et al., 1995)

Another design strategy, the set-based approach, has been the subject of a number of publications over the past 20 years. It is one of the pillars of lean thinking applied to product development, again, observed particularly in the automotive industry through companies such as Toyota, Honda, or Denso. Here, engineers may reason and communicate about acceptable range of parameter's values instead of single best value at a time. Set-based design allows windows of possibilities to align gradually and therefore the best of all worlds to be projected. It is rather a convergence process than an evolution (Sobek & Ward, 1996). Participants bring sets of possibilities to the table and juxtapose them to find intersection of feasibility rather than successively criticizing and modifying a single option (Liker, Sobek II, Ward, & Cristiano, 1996). Figure 2.6 illustrates the approach.

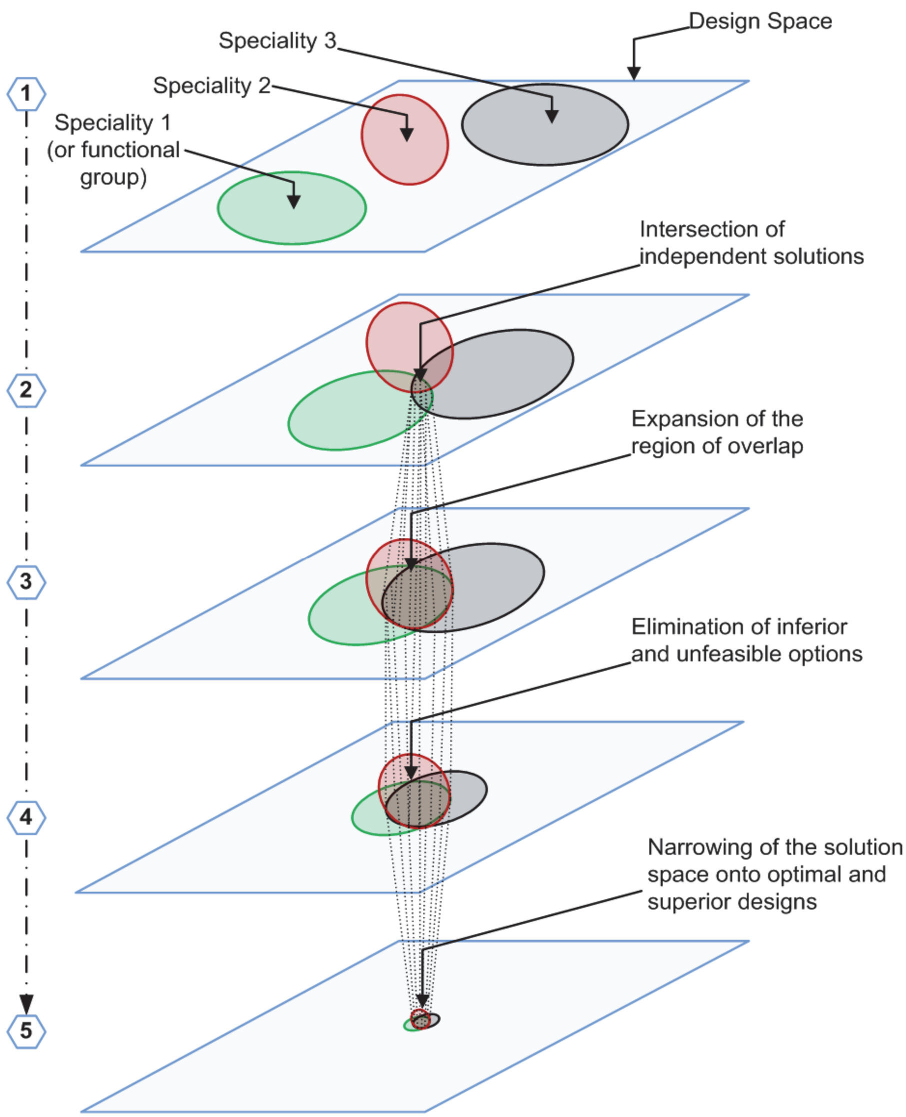


Figure 2.6: Set-based approach to the design of a complex product. Adapted from (Bernstein, 1998)

Set-based approach to problem solving has already proven to be efficient in some simple problems like selecting a group meeting time. Participants may submit their preferences and then the meeting organiser finds the most convenient time in the intersection of all, i.e. set-based solving. In contrast, point-based solving may involve either: participants compromising a meeting time one after the other until a satisfactory time emerges, or participants having a meeting to decide the meeting time, or finally, some powerful members forcing everyone to comply with a selected time. Sobek, Ward and Liker (1999) described the three principles of SBCE which, according to Ghosh and Seering (2014), have remained the same used for SBCE discussions and implementations across the research literature and industrial applications.

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

Several methods like the morphological chart (Cross, 1989), the method of controlled convergence (Pugh, 1991), the Design-Build-Test cycle (Wheelwright & Clark, 1992), the fuzzy inference based concept convergence process (Augustine, Yadav, Jain, & Rathore, 2010) and the Configurable Component based platform i.e. product platform strategy (Wahl & Johannesson, 2010) share strong similarities with SBCE (design strategy) in the sense that they all use the exploration of multiple alternatives to converge within the design space or the design *bandwidth*[2]. The main specificity of SBCE is twofold: (1) In SBCE, speciality groups can independently analyse their design options (sets of design alternatives) then intersect at integration events which then eliminates the iterative path that is problematic in point-based approach (Bernstein, 1998; Sobek & Ward, 1996); (2) SBCE delays decision to learn by experimentation (extensive prototyping) and additionally front-load the design/development (reuse/recycling of existing knowledge) before narrowing the design space by elimination of unfeasible designs (Morgan & Liker, 2006; Ward & Sobek, 2014). Prototyping, learning and the reuse of existing well-structured information and knowledge are therefore important aspects of SBCE. To elaborate, Ghosh and Seering (2014) extracted seven characteristics of set-based product development after thoroughly analysing the literature on set-based thinking in the engineering community and beyond: (1) Emphasis on frequent, lo-fidelity prototyping; (2) Tolerance for under defined system specifications; (3) More efficient communication among subsystems; (4) Emphasis on documenting lessons learned and new knowledge; (5) Support for decentralized leadership structure and distributed, non-collocated teams; (6) Supplier/subsystem exploration of optimality and; (7) Support for flow-up knowledge creation. The seven characteristics are used to form a framework for analysing the research works that exhibit set-based practice. As a result of the review, Ghosh and Seering (2014) acknowledge the fact that set-based design is not formally defined and they point out the tendency of the majority of authors to mainly study the set-based process as perceived and inspired from Toyota's practice and philosophy. The observations are then refined to distill two fundamental overarching principles that govern Set-Based Design (SBD) i.e. (**A**) Considering sets of distinct alternatives concurrently and, (**B**) delaying convergent decision-making. It is argued that the principles are fundamental in the sense that they can manifest themselves in all phases of the design process, not limited to the conceptual phase or the interface with detailed design phases (Ghosh & Seering, 2014). These authors note that it is not possible to guarantee that the two principles are the only ones governing SBD, but they are sufficient to contrast SBD and traditional Point-Based Design (PBD) by defining one as the negation of the other. As such, propositional logic is used to express $\mathbf{SBD} \equiv \mathbf{A} \wedge \mathbf{B}$, then, by

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

considering PBD is simply "not SBD", PBD is formed as the negation of the conjunction. This, by De Morgan's law, is the disjunction of the negations: **PBD ≡ ¬SBD = ¬(A ∧ B) = ¬A ∨ ¬B**, which means that the lack of either principle A or principle B will rule out a design/development process as set-based. Both principles have to be followed to make a design/development process set-based. Ghosh and Seering (2014) conclude their study by listing a number of research areas requiring exploration. In details, it is said that it will be constructive to determine what factors and situations are more suitable for the application of SBD vs. PBD, understanding the related cost, performance and trade-off. In addition, it is noted that research need to better identify works that are not explicitly associated with set-based but which disclose characteristics of SBD and can actually improve its understanding and implementation. To continue on Ghosh and Seering' path, the remaining part of this chapter concentrates on a systematic literature review of SBCE using a new SBCE analysis framework.

2.2.2 A new SBCE systematic review framework

Researchers usually perform literature reviews by analysing existing research content that exhibit nominal characteristics of the topic of interest. The material studied typically takes the form of text and figures that constitutes a publication or a document. Books, textbooks and electronic content found in library catalogues and the Internet provide the foundational knowledge on the subject, as targeted for a wider audience. In-depth content and contribution made available by researchers through academic research publications are generally found in research databases in the form of journal articles, conference papers, research reports and other documentation. These, identified using keyword searches, usually provide the researcher with a deeper understanding of the subject as well as the means to map and assess the body of knowledge on the topic in its different aspects. By backtracking through references found in the key publications, it is possible for the researcher to identify additional publications which are relevant to the research but were not found using the previous means. As a result of the process, researchers will traditionally produce narrative reviews analysing and assessing the knowledge on the topic in order to specify a research question which will in turn develop and extend the knowledge on some, the whole or unknown facets of the topic. Although many steps of the process as described can be recognized as essential parts of a literature review, traditional narrative reviews have been criticized for their lack of systematic approach, explicitness, thoroughness, transparency, reproducibility and reliability assuming the review can be biased by the researcher (Cooper, 1998; Fink, 2005; Tranfield et al., 2003). The quality of evidences supporting interpretations and inferences in a research work and the resulting influences on practitioner's decision-making and action can be questioned. To mitigate the issue, evidence-based approaches have developed in the medical science and healthcare in order to eliminate the dependency on "implicit, idiosyncratic methods of data collection and interpretation and the resulting poor-quality evaluations of the literature that had sometimes led to inappropriate recommendations" Tranfield et al. citing (Cook, Greengold, Ellrodt, & Weingarten, 1997a; Cook, Mulrow, & Haynes, 1997b; Greenhalgh, 1997). To give an idea of the magnitude of the concern, Tranfield et al. (2003) mention Smith (1991) who assessed the "overall wisdom of much of medical science" in 1991 and reported that only 15% of medical interventions were actually supported by solid scientific evidence. As a consequence, taking on systematic review is now considered a "fundamental scientific activity" (Cooper, 1998; Fink, 2005; Mulrow, 1994). Tranfield et al. (2003) citing (Cook et al., 1997b) state that "systematic reviews differ from traditional narrative reviews by adopting a replicable, scientific and transparent process, in other words a detailed technology, that aims to minimize bias through exhaustive literature searches of published and unpublished studies and by providing an audit trail of the reviewers decisions, procedures and conclusions". This view is supported by Cooper and Fink (Cooper, 1998; Fink, 2005). A step by step methodology is proposed to perform a systematic review, which comprises stages including phases as listed below (NHS, 2001; Tranfield et al., 2003):

Stage I - Planning the review:

- Phase 0 - Identification for the need for a review;
- Phase 1 - Preparation of a proposal for a review;
- Phase 2 - Development of a review protocol;

Stage II - Conducting a review:

- Phase 3 - Identification of research;
- Phase 4 - Selection of studies;

- Phase 5 - Study quality assessment;
- Phase 6 - Data extraction and monitoring progress;
- Phase 7 - Data synthesis;

Stage III - Reporting and dissemination:

- Phase 8 - The report and recommendations;
- Phase 9 - Getting evidence into practice.

SBCE systematic review is performed in this thesis by following the proposed evidence-based approach and methodology.

2.2.2.1 Stage I – Planning the review

Planning the review is the initial stage of the systematic review which consists of three phases geared towards the delimitation of the scope of the review and the definition of the protocol by which the review will be tackled. In the context of this thesis, the review panel is formed by the supervisors, the collaborators and the peer-reviewers during the submission for publication. The theoretical, practical, and methodological history debates surrounding the fields of lean thinking, lean production, lean product and process development (LPPD) and the sub-field of interest, set-based design (SBD) / set-based concurrent engineering (SBCE) have gradually been expounded in the previous sections of this chapter. This has been narrowed to the necessity to perform the systematic review of SBCE in order to explicitly, transparently, reliably and thoroughly assess the literature pertaining to SBCE in a reproducible manner. The aim of the systematic review is to analyse the literature as it relates to the characterisation and confirmation of SBCE key enablers and catalysts in developing a holistic model that can support the transition to SBCE from the current PD practice, conventional tools and assets. This can be formulated into a review question which, according to Tranfield et al. (2003), is critical when planning evidence-based systematic reviews:

What are the SBCE literature characteristics, enablers and catalysts for proposing/developing holistic models and methodologies intended to support the transition to SBCE from the current PD practice, conventional tools and assets?

SBCE theoretical grounds have previously been expressed while extracting important aspects of the approach such as the exploration of a design space, the extensive use of prototypes and the very specific concurrent engineering practices that holds alternative designs long into the development process by delaying decision. From a practical PD standpoint, handling multiple design alternatives during the development process usually calls for configurability of the product or the platform as prerequisite (Claesson, 2006; Claesson & Johannesson, 2006; Erens, 1996; Hegge, 1995; Männistö, Peltonen, Soininen, & Sulonen, 2001; Sabin & Weigel, 1998; Van Veen, 1991; Wortmann & Erens, 1995). For these reasons, the combination of keywords selected to query the research databases are listed below.

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

The truncation of some of the keywords is done on purpose to allow the stemmer of the search engines to systematically locate publications containing related terms. For example, the keyword prototyp* allows to fetch publications containing either prototype or prototyping. Similarly, configur* will search for configuration, configurable, configured, etc. This is usually handled by the stemming algorithm embedded into the search engine but can sometimes show ineffective for languages with simple morphology like English (Kamps, Monz, De Rijke, & Sigurbjörnsson, 2003). Hence the use of truncation. The search engines also ignore the "-" in hyphenated compound words such as "set-based" by returning both cases with or without the hyphen. As this work pertains to engineering science and the related cognitive and social sciences, the research databases selected for the data extraction are **Compendex** and **Inspec** (EBSCO) for engineering research publications and **Web of Science** (Thomson Reuters) to cover the broader landscape of sciences relating to design as a cognitive and social science. Databases like Proquest (ABI Inform) which contain dissertations and other institutional publications are not included to focus on peer-reviewed works. This is done assuming backtracking through the peer-reviewed will allow to consider the related comprehensive institutional publications. Indeed, backtracking is important as it mitigates the limitations of relying on keyword searches. It supports exploring new areas of the subject which are not otherwise nominally related to the topic as queried. Once the review question, the keywords and the target sources for the data collection are defined, it is instructed to continue on documenting the review protocol by discussing the publications inclusion and exclusion criteria, the explicit step by step plan that helps to protect objectivity during the review and the framework by which the selected publications will be systematically analysed (Cooper, 1998; Fink, 2005; Tranfield et al., 2003). For the current review:

1. The pool of applicable publications is extracted from the target research databases using the selected keywords and combination. New publications alerts are set up for each combination of keywords with the purpose of continually feeding the pool with recently published contributions. This runs until the end of the review process and beyond;

2. The sets of records are organised into data extraction forms (spreadsheets) following a template of relevant fields/columns that comprises the authors, authors affiliation, title, abstract, year of publication, classification (research area), source (name of the journal or conference proceedings) and the type of document (article vs. proceedings paper). According to Tranfield et al. (2003), data extraction forms are preferred because they reduce human error and bias by supporting a comprehensive, objective and systematic data synthesis which in turn enable audit trails of the reviewer's decisions, procedures and conclusions;

3. The records in the data extraction forms are then compared to eliminate duplicate publications as independently extracted from each database. The resulting unique records are merged and collated into a single form (spreadsheet) in order to perform the analysis from a single version of the truth;

4. Each title and abstract is carefully read and the research area classification is considered to perform the preliminary assessment and furthermore assign a category as inspired by (León & Farris, 2011; Nissen, 1996) and defined below. The full text paper is scanned every time the title and abstract do not provide enough information to readily assign a category to the publication. In practice, the process is quite iterative as a publication may receive a category based upon the content of the abstract, which may then require an update following thorough examination of the full text paper. This flexibility is embedded into the form as well as the automatic update of the generated pivot charts.

    - **Category 0**: Not relevant to the research because of the content and the classification of the research area e.g. content related to set theory and pure level set methods, classifications such as Graph theory, Set theory, Information Theory and Signal processing, Mathematics, Chemistry, Imaging science & Photographic Technology, etc. Records of all exclusions are kept into the form for traceability purposes;
    - **Category 1**: Methods/Techniques that facilitates SBCE e.g. Fuzzy sets, interval sets, CAD parameters, Computational Design Synthesis;
    - **Category 2**: Blend of SBCE principles/techniques into other approaches to provide new methods/approaches to the design/development process e.g. multidisciplinary design optimization;
    - **Category 3**: Lean in general with consideration of SBCE;
    - **Category 4**: Application/confirmation of SBCE principles, methods and techniques;
    - **Category 5**: Development of SBCE theories, models and methodologies for its practical implementation;

5. Category 0 publications are filtered out to focus on the remainder which forms the subset of publications that are relevant to the SBCE systematic review. Full text papers not read until this step are examined in order to confirm the preliminary category. Quantitative charts are generated from the initial data, then data related to the journal index (Impact

factor, Eigenfactor score, total cites) is added to the sources to qualitatively assess the contributions;

6. Category 5 publications, directly involved with the review question, are sorted out to get classified through the lens of a newly designed dual analysis framework. Thorough examination and assessment of the content of these Cat-5 publications is performed by describing the contribution of the research as it relates to the review question;
7. The synthesis is then refined to precisely report on the findings, recommendations and future research directions.

A new SBCE analysis framework is proposed in this thesis with the goal of assessing what research paradigms and methods are used in SBCE research to generate new knowledge about SBCE on one side and, what coverage of the engineering design process is available on the other side when it comes to proposing/developing holistic models and methodologies intended to support the transition to SBCE from the current practice. SBCE belongs to the lean philosophy and as such, can be assessed through the fundamental continuous improvement cycle i.e. PDSA, **Plan-Do-Study-Act** (Deming, 2000), as well as the fundamental value creation cycle i.e. LAMDA, **Look-Ask-Model-Discuss-Act** (Ward & Sobek, 2014). An additional layer may also involve mapping each step of these cycles to the generic creative design process (Formulation-Synthesis-Analysis-Evaluation-Documentation-Reformulation) (Howard, Culley, & Dekoninck, 2008) as perceived from the SBCE perspective i.e. **Explore** (formulate, map the design space) – **Generate** (synthesize/analyse alternative designs) – **Learn** (evaluate, document, communicate) – **Refine** (overlap design options, eliminate weak options, reformulate). The practical implementation cycle steps aligned with the SBCE design process steps altogether result into four dimensions/areas for analysing the literature. These dimensions/areas can furthermore be decomposed into segments representing the granular concepts, approaches, techniques and catalysts for which the usage and implementation in the literature can be explored towards proposing/developing holistic models and methodologies intended to support the transition to SBCE. The proposed analysis framework is shown below in a continuous improvement cycle form. The framework is stored in the workbook in a tabular form, which is then used as a pick list to assign dimensions/areas and segments to a Cat-5 research publication examined through the review. Automation is built in the form (worksheet) to generate and update pivot charts, which provides the required flexibility throughout the review process i.e. a process of exploration, discovery and development (Cooper, 1998; Fink, 2005; Tranfield et al., 2003).

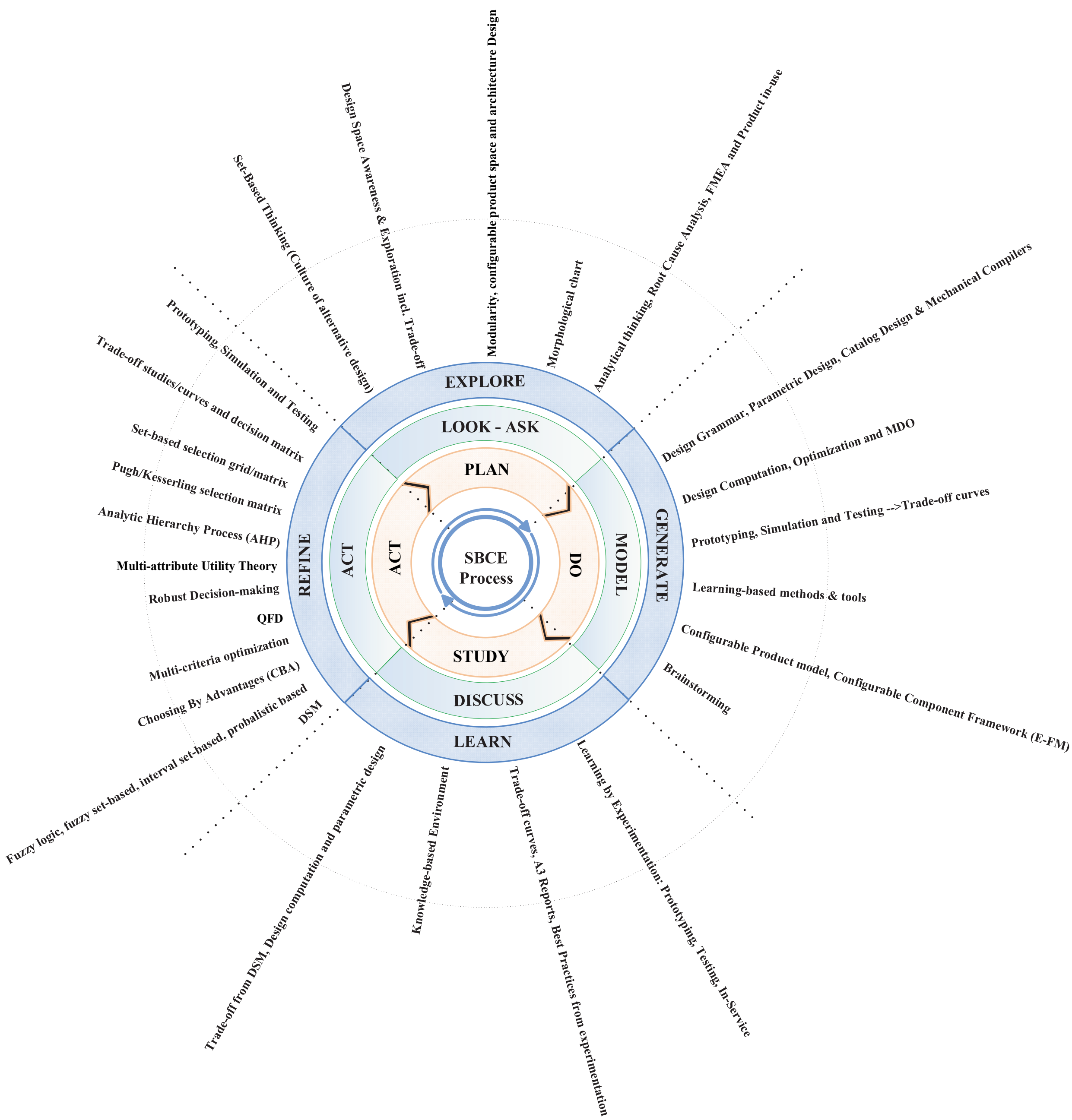


Figure 2.7: Set-based design process analysis framework

Another way to examine the literature is to identify the research paradigm and the methods used in a research work. The aim is to objectively perceive the purpose of the research, the type of inquiry, inference and construction done by the research work as well as the typical outputs and theory-building vs. practical implications that can be expected from the research (Hart, 1998; Hoepfl, 1997). Hoepfl (1997), citing (Patton, 1990) states that “phenomenological inquiry, or qualitative research, uses a naturalistic approach that seeks to understand phenomena in context-specific settings, while logical positivism, or quantitative research, uses experimental methods and quantitative measures to test hypothetical generalizations. Each represents a fundamentally different inquiry paradigm, and researcher actions are based on the underlying assumptions of each paradigm”. For instance, qualitative research is predominantly interpretative, inductive, emerging meaning and themes from the data analysis, which is collected through interviews, observations and experience (Creswell, Hanson, Clark Plano, & Morales, 2007; Patton, 1990; Strauss & Corbin, 1990). The researcher is the instrument for the data collection and there are special criteria to judge the validity, reliability and trustworthiness of the research (Glaser, 1978; Golafshani, 2003; Patton, 1990). The research method(s) in particular reveal(s) the type of inquiry and therefore the type of answers a research work can provide. For example, narrative research is chronological/story-oriented in nature, answering questions on how life experiences and events unfold over time (Creswell et al., 2007). Case study research is to answer in-depth and descriptive questions such as “How” and “Why” (Creswell et al., 2007; Yin, 2013), developing insight into an issue from different cases or a unique case. Grounded theory deals with process, action and interaction questions, focusing on the phased and combined effect of a phenomenon or change, while phenomenology develops answers on what is at the essence of the phenomenon (Creswell et al., 2007; Strauss & Corbin, 1990). Action research typically involves the researcher in a community, developing understanding of phenomena and answering questions to proactively transform the community or to define how change can occur in the community (Creswell et al., 2007; Paillé & Mucchielli, 2016). From an epistemological standpoint, researchers fundamentally take stances which can be explicit or rather implicit. Constructivist approaches for example perceive knowledge as a human and social construction by claiming that truth is relative and it is dependent on one’s perception (Baxter & Jack, 2008), while in rationalist approaches, truth is not sensory-related but intellectual and deductive, proceeding solely through the reason (Bourke, 1962). Constructivism proceeds through knowledge as socially constructed to extend it based upon a referential paradigm, which can shift as time progresses and new knowledge is acquired through the same or rather different stance (Kuhn, 1970). Pragmatism, to continue, goes beyond describing and reflecting the reality to rather "emphasize the practical application of ideas by acting on them, extending the reality, to actually test them in human experiences" (Gutek, 2013). The aim here is not to review epistemological stances and research paradigms, which can be found in regular dictionaries of philosophy and books/textbooks about research design and research methods. The figure below shows the proposed SBCE literature research paradigm analysis framework.

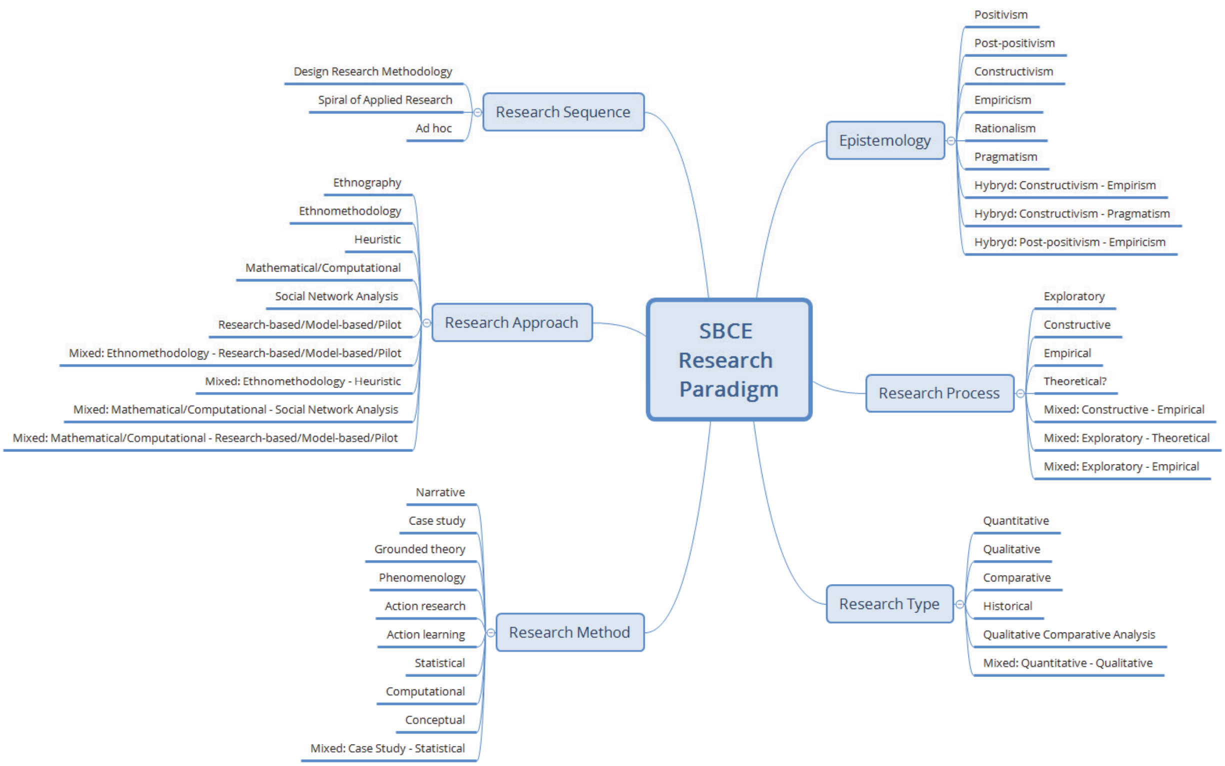


Figure 2.8: Research paradigm analysis framework.

The above research paradigm framework together with the SBCE design process framework described earlier form the proposed dual framework for examining the Cat-5 SBCE research publications.

2.2.2.2 Stage II – Conducting a review

The main activities in conducting the review have been described previously while designing the review protocol. These include the identification of the research (research field and research question) i.e. phase 3, the criteria for selecting studies and arranging them into categories/segments (keywords synthesis, data collection procedure, data extraction forms and monitoring process, inclusion/exclusion criteria, framework for the analysis) i.e. phase 4, the means by which the quality of a study can be assessed (dual framework including research design/paradigm analysis, qualitative assessment) i.e. phase 5 and the data extraction and monitoring process i.e. phase 6. This section on conducting the review focuses on the actual results from extracting, refining and categorizing the SBCE research publications data (data synthesis) i.e. phase 7.

The extraction results into a total of **1733** publications. After duplicate records are removed, the remaining **921** records are collated to form the pool of publications to categorize (0-5) as described in the review protocol. The table below displays the outcome of the initial data extraction as specified in the review protocol.

Table 2.2: Number of hits per keyword combination

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

The timespan for the search is from 1987, the year in which publications on the Japanese product development practices began to appear, to 2017 which represents the end of the data collection pertaining to this review. It should be noted that Web of science database searches are limited from 1989 onward. The 921 research publications are categorized following the process described in step 4 of the review protocol. 83% of these records (767 publications) have received the category 0, which means they are not relevant to the actual topic of the review after analysing the content and the classification of the research area e.g. content related to set theory and pure level set methods, classifications such as Graph theory, Set theory, Information Theory and Signal processing, Mathematics, Chemistry, Imaging science & Photographic Technology, etc. The figure below shows the distribution of the **154** publications relevant to SBCE.

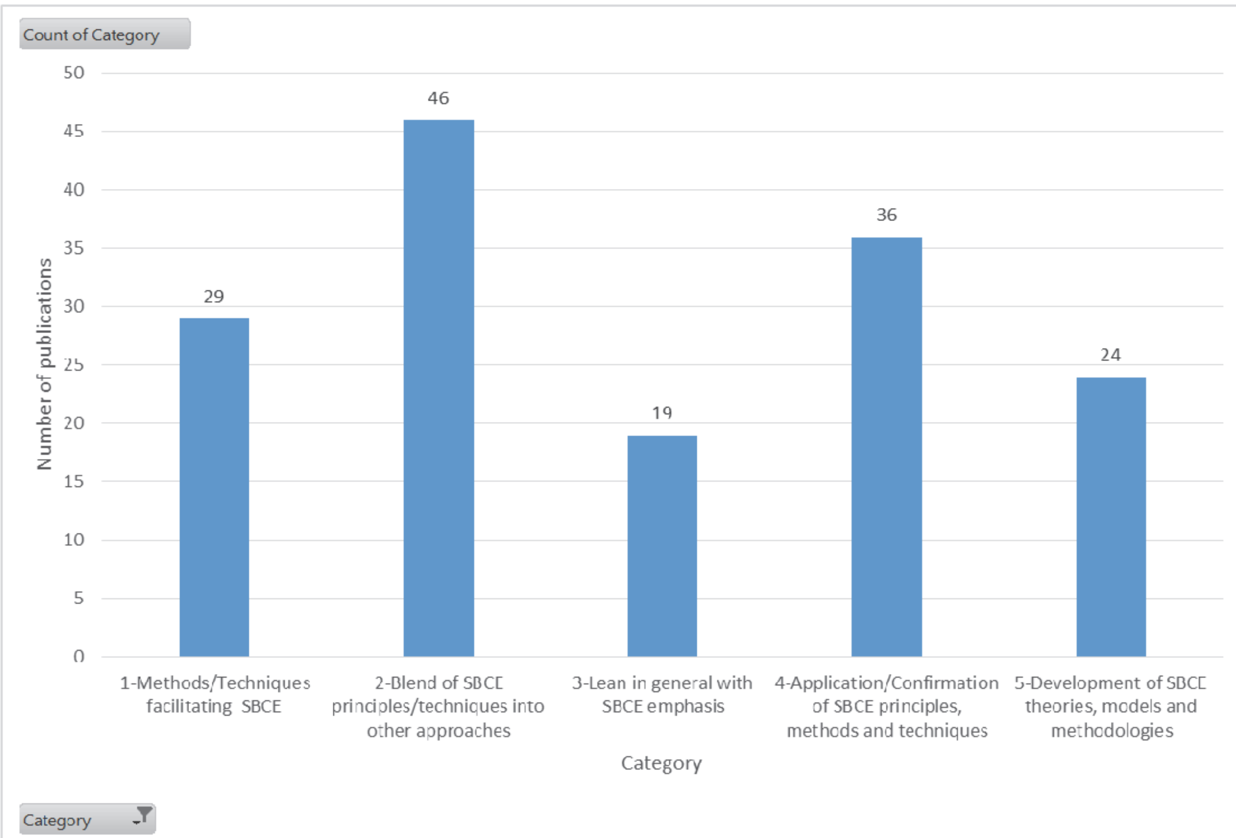


Figure 2.9: Distribution of Category 1-5 publications (relevant to SBCE)

The majority of publications pertaining to SBCE i.e. 46 of the 154 (30%) deal with research works blending SBCE principles/techniques into other approaches to provide new methods/approaches to the design/development process. The publications in this category 2 frequently focus on the design synthesis and selection process by exhibiting how the distinct approach/concept or technique adequately fits the SBCE concept generation, exploration and selection process. This denotes a growing interest in SBCE from many field research areas as well as the pervasive influence of SBCE especially on methods and techniques for early stages in the development process. Examples include the combination of SBCE principles and techniques with **multi-objective problem/multidisciplinary optimization** (Avigad & Moshaiov, 2009, 2010; Hannapel & Vlahopoulos, 2014; Hannapel, Vlahopoulos, & Singer, 2012; Moshaiov & Avigad, 2007; Sasaki & Ishikawa, 2015), **Constraint Satisfaction Problem (CSP)** (Canbaz, Yannou, & Yvars, 2011; Inoue et al., 2012; Inoue, Nahm, Tanaka, & Ishikawa, 2013a; Ishikawa & Nahm, 2005; Kizer & Mavris, 2014; Nahm & Ishikawa, 2005; Nahm, Ishikawa, & Yang, 2007; Qureshi, Dantan, Bruyere, & Bigot, 2010; Wang, Yannou, Alizon, & Yvars, 2013; Yannou, Yvars, Hoyle, & Chen, 2013), **Computer Aided technologies (CAx)** (Becker & Wits, 2015; Cho, Lee, & Bae, 2014; ElMaraghy & Jack, 1993; Essamlali, Sekhari, & Bouras, 2016; Toche, Pellerin, Fortin, & Huet, 2012), **Game Theory** (Kerga, Rossi, Taisch, & Terzi, 2014a; Kerga et al., 2014b; Pourabdollahian, Taisch, & Kerga, 2012) and **Bayesian networks** (Matthews, Klatt, Seepersad, Haberman, & Shahan, 2014; Shahan & Seepersad, 2009; Shahan & Seepersad, 2012) to name a few. Cat-1 is very similar to Cat-2 with the only difference that Cat-1 focuses on the method itself (e.g. fuzzy set-based approach, interval set propagation, method of imprecision, etc.) and the means by which it can facilitate SBCE e.g. (Finch & Ward, 1997; Otto & Antonsson, 1995; Ward, 1989). The authors in Cat-1 usually have equivalent publications in Cat-2 where the novel approach blending SBCE into the expert method is forwarded but the two categories are not always easy to separate on this sole basis. Cat-1 examples include (Antonsson & Otto, 1995; Canbaz, Yannou, & Yvars, 2014; Hernandez-Luna, Moreno-Grandas, & Wood, 2010; Hernandez-Luna & Wood, 1994; Kawakami, Kami, Ishikawa, & Xiao, 2016; McKenney, Gray, Madrid, & Singer, 2011; Ong, Sun, & Nee, 2003; Ong & Nee, 1998; Panchal, Gero Fernández, Paredis, Allen, & Mistree, 2007; Qureshi, Dantan, Bruyere, & Bigot, 2014; Shan & Wang, 2003; Wang & Shan, 2004; Zhai, Khoo, & Zhong, 2009). One can therefore argue that Cat-1 and 2 should merge into a single category about discrete methods that facilitate SBCE.

Cat-4 comes in second position with 36 of the 154 publications (23%). Cat-4 deals with publications that report on the application of SBCE principles, methods and techniques as synthesized from the literature in order to improve understanding of SBCE on one hand and, strengthen the SBCE performance predictions on the other hand. Examples include (Araci, Al-Ashaab, & Maksimovic, 2015; Bertoni, Levandowski, Isaksson, & Larsson, 2016; de Souza & Borsato, 2016; Elhariri Essamlali, Sekhari, & Bouras, 2017; Ford & Sobek, 2005; Giachetti, 1997; Heikkinen, Stolt, Elgh, & Andersson, 2016; Inoue, Nahm, Tanaka, & Ishikawa, 2013b; Ishikawa & Inoue, 2009; Kennedy, Sobek, & Kennedy, 2014; Kerga, Khan, & Arias, 2012; Kerga, Taisch, & Terzi, 2012; Landahl, Levandowski, Johannesson, & Isaksson, 2016; Landahl, Raudberget, & Johannesson, 2015; Maksimovic, Al-Ashaab, Sulowski, & Shehab, 2012; Maulana et al., 2016; McKenney & Singer, 2014; McKenney, Kemink, & Singer, 2011; Neeley, Lim, Zhu, & Yang, 2013; Parrish, Wong, Tommelein, & Stojadinovic, 2008a; Raudberget, 2010a, 2010b; Raudberget & Sunnersjö, 2010; Rocha, Affonso, & De Oliveira, 2012, 2013; Takai, 2010). These Cat-4 publications are distinguished from Cat-5 as they do not attempt to develop actual SBCE theories, models and methodologies. Cat-5 publications, which is the focus of this review, will next be examined in details through the proposed dual analysis framework. The Cat-5 publications accounts for 16% of the total 154 publications identified as relevant for the SBCE systematic review.

2.2.2.3 Stage III – Reporting and dissemination

Reporting and dissemination in this review follows the NHS guidelines (NHS, 2001). Tranfield et al. (2003) for instance state that the stage should answer questions like “What is the age profile of the articles?” “Can the fields be divided into epochs in terms of volume or orientation of study?” “Do simple categories divide up the field?” etc. The age profile of the Cat-1 to 5 relevant to the SBCE systematic review is shown below.

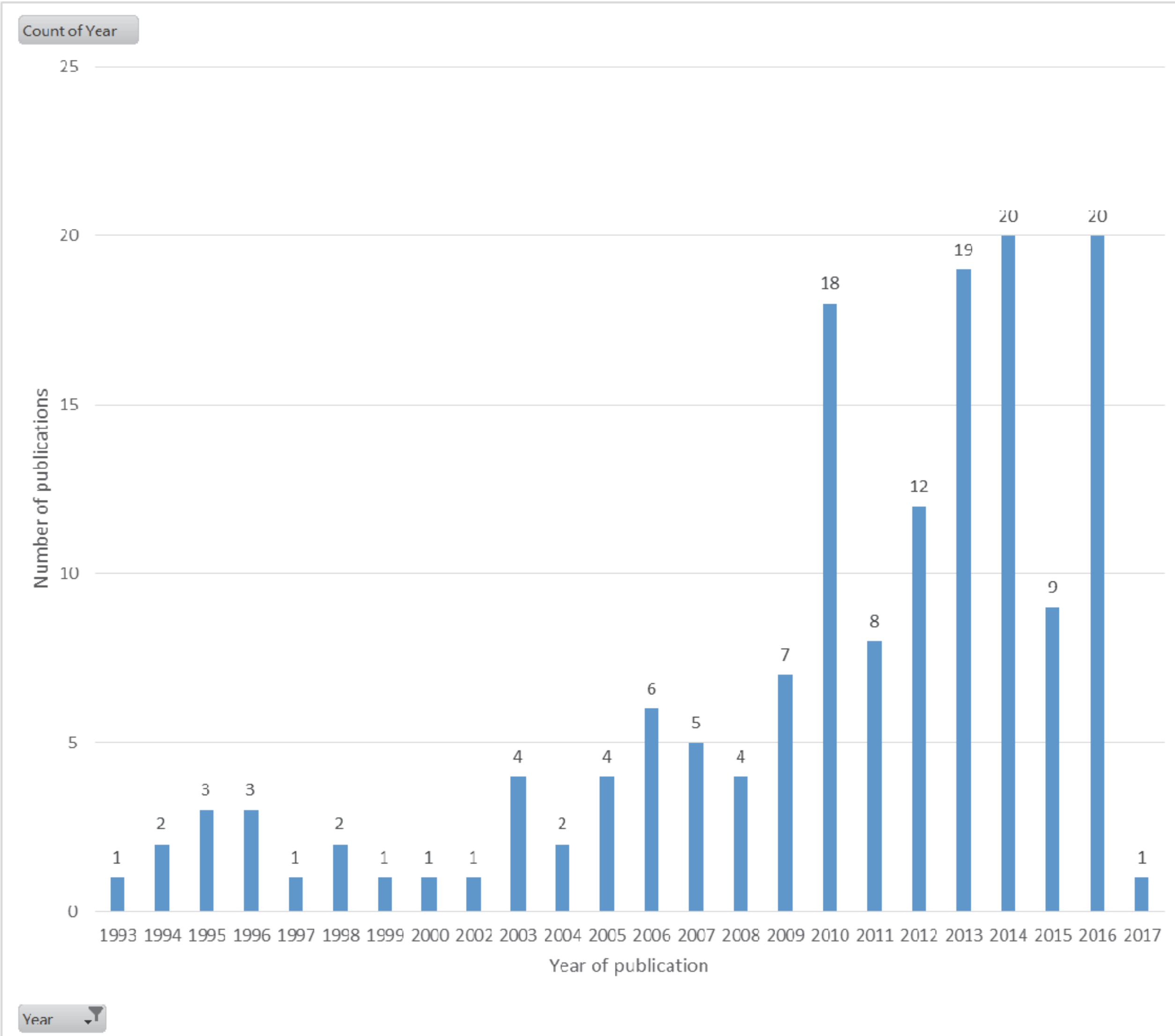


Figure 2.10: Age profile of Category 1-5 publications

The profile discloses a fluctuating growth of SBCE publications from 1993 onward with a proliferation starting in 2010. There are two potential reasons for the relative absence of SBCE related publications between 1987 and 1993. Firstly, set-based concurrent engineering, as it refers to Toyota's practice, was coined by Ward et al. (1994) in their landmark paper presented at the proceedings of the 1994 ASME Design Technical Conferences in Minneapolis, USA. Secondly, even though early 90's research on engineering design calculations with fuzzy parameters, labeled interval calculus and other methods like the Method of Imprecision (MoI) and constraint satisfaction clearly involved set-based reasoning (Antonsson & Wood, 1989; ElMaraghy & Jack, 1993; Hernandez-Luna & Wood, 1994; Hyvönen, 1992; Tommelein, 1989; Ward, 1989; Wood, Otto, & Antonsson, 1992), they did not entail the holistic SBCE philosophy and principles, institutional knowledge capture and reuse advocated to enable a superior PD process (see previous descriptions of LPD and SBCE). In addition, these early research works involving set-based methods are not always nominally identified as such, which is the reason why some are captured by the keywords search and some other are not. The complimentary publications are discussed here as discovered through the references backtracking process explained during the design of the review protocol. The proliferation of SBCE research in the 21st century and especially the present decade can both be explained by a growing interest in the field, and the compelling socioeconomic factors in the aftermath of the global financial crisis (2007-2008). These factors have increasingly been demanding responsive, flexible, agile and lean product development processes for companies to stay competitive or simply, viable.

The age profile chart shows evidences of a growing popularity and interest in SBCE but it provides no information on the maturity and importance of the field research. Assessment variables that can support such analysis include the ratio between peer-reviewed vs. non-peer-reviewed works, the count of publications in journals and the ranking of the journal by indexes such as the Total Cites, Impact factor (Journal Citation Reports® published by Thomson Reuters) and the Eigenfactor® score (eigenfactor.org). As explained during the design of the protocol, this review concentrates on extracting peer-reviewed works and subsequently using the references backtracking to explore additional non-peer-reviewed. The pool of 154 SBCE relevant publications therefore only include journal articles (40%) and proceedings papers (60%). The chart below shows the distribution per medium of publication by year.

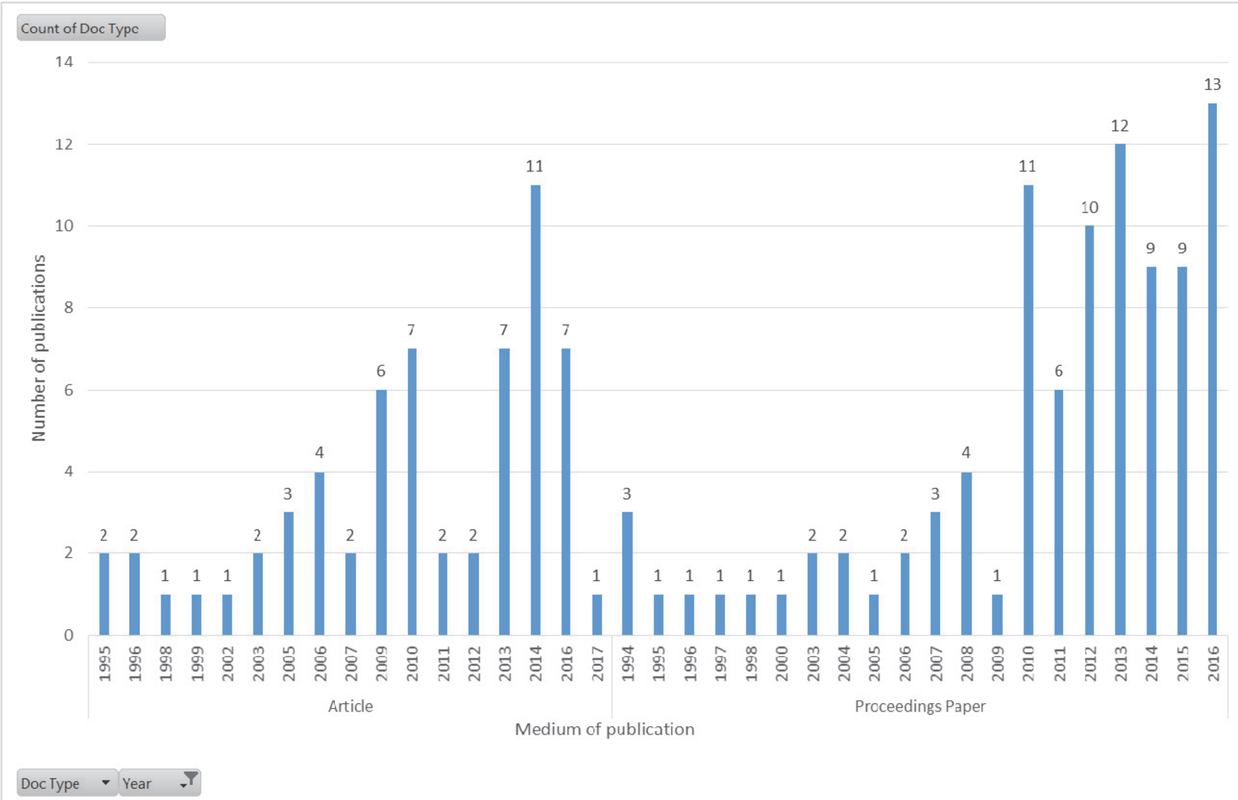


Figure 2.11: Medium of publication of Category 1-5 research work by year

The relatively small percentage of journal publications indicates a low theoretical development of the field which is usually acknowledged within the LPD and SBCE research community. Although one may conversely argue that theoretically mature research fields can be found publishing more in conference proceedings than journals, e.g. for timely reasons, it is concurred herein with León and Farris (2011) that the relative amount of publications in scientific journals remains an objective indicator of fundamental and theoretical development into a field. The chart below shows the variety of journals (36) that have published SBCE related works. This variety is the result of SBCE being explored from diverse perspective i.e. knowledge domains.

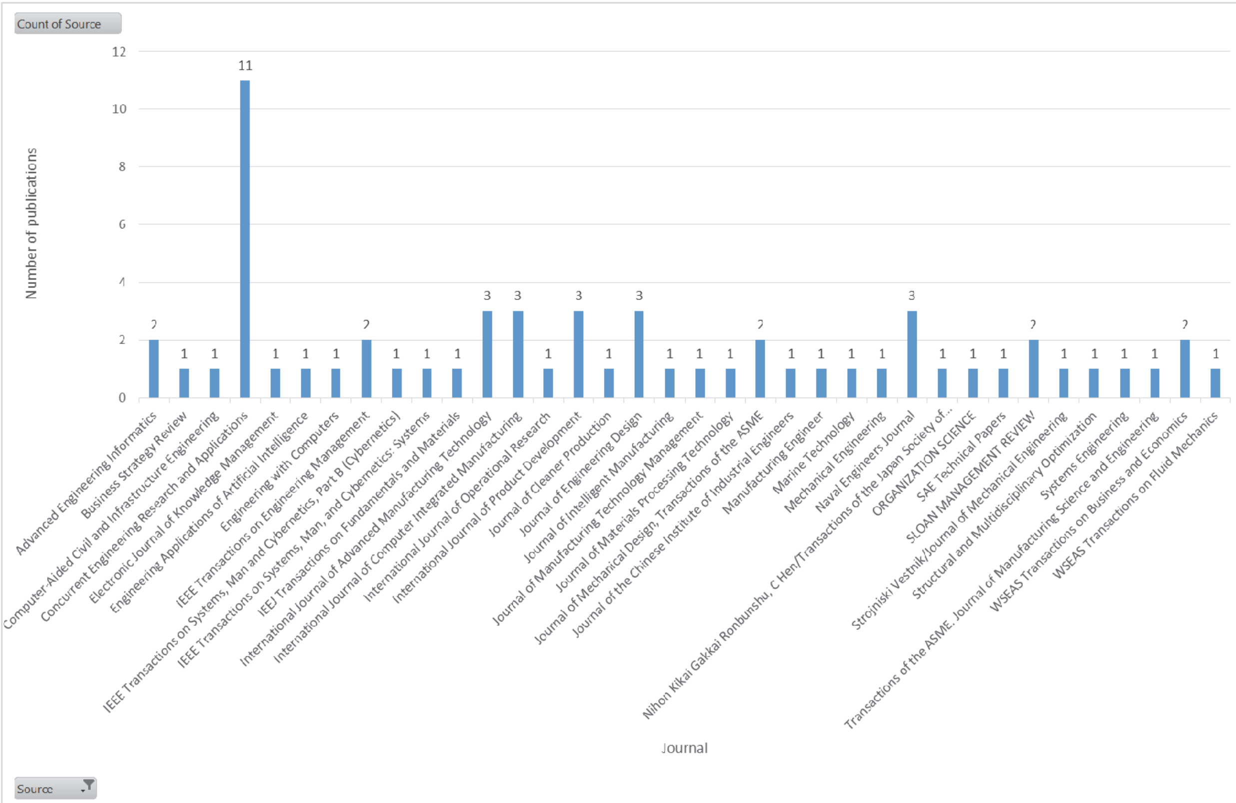


Figure 2.12: Distribution of Category 1-5 journal publications

Concurrent Engineering Research and Applications appears to be the journal with most (11) of the 61 journal publications, far followed by the Journal of Engineering Design (3), the International Journal of Advanced Manufacturing Technology (3), the International Journal of Computer Integrated Manufacturing (3), the International Journal of Product Development (3) and the Naval Engineers Journal (3). The charts below display the Total Cites, Impact factor and Eingenfactor score of each of the journal that published SBCE related work as extracted for the review. As explained during the design of the review protocol, these criteria are not used to include or exclude a publication and they are discussed here only as a mean to assess the relevance, importance, breadth and depth of the SBCE research from the overall research community perspective.

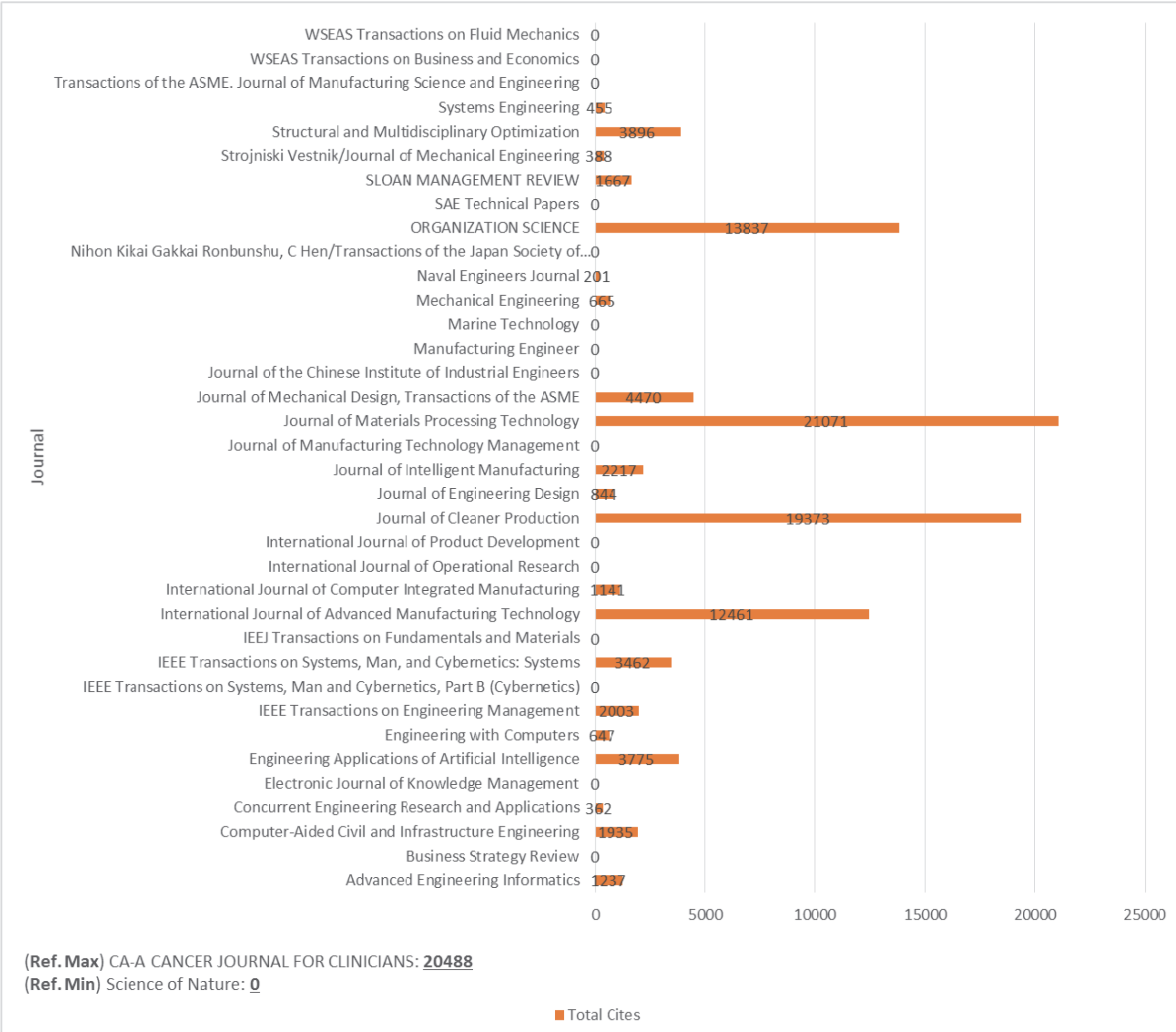


Figure 2.13: Category 1-5 journal Total Cites

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

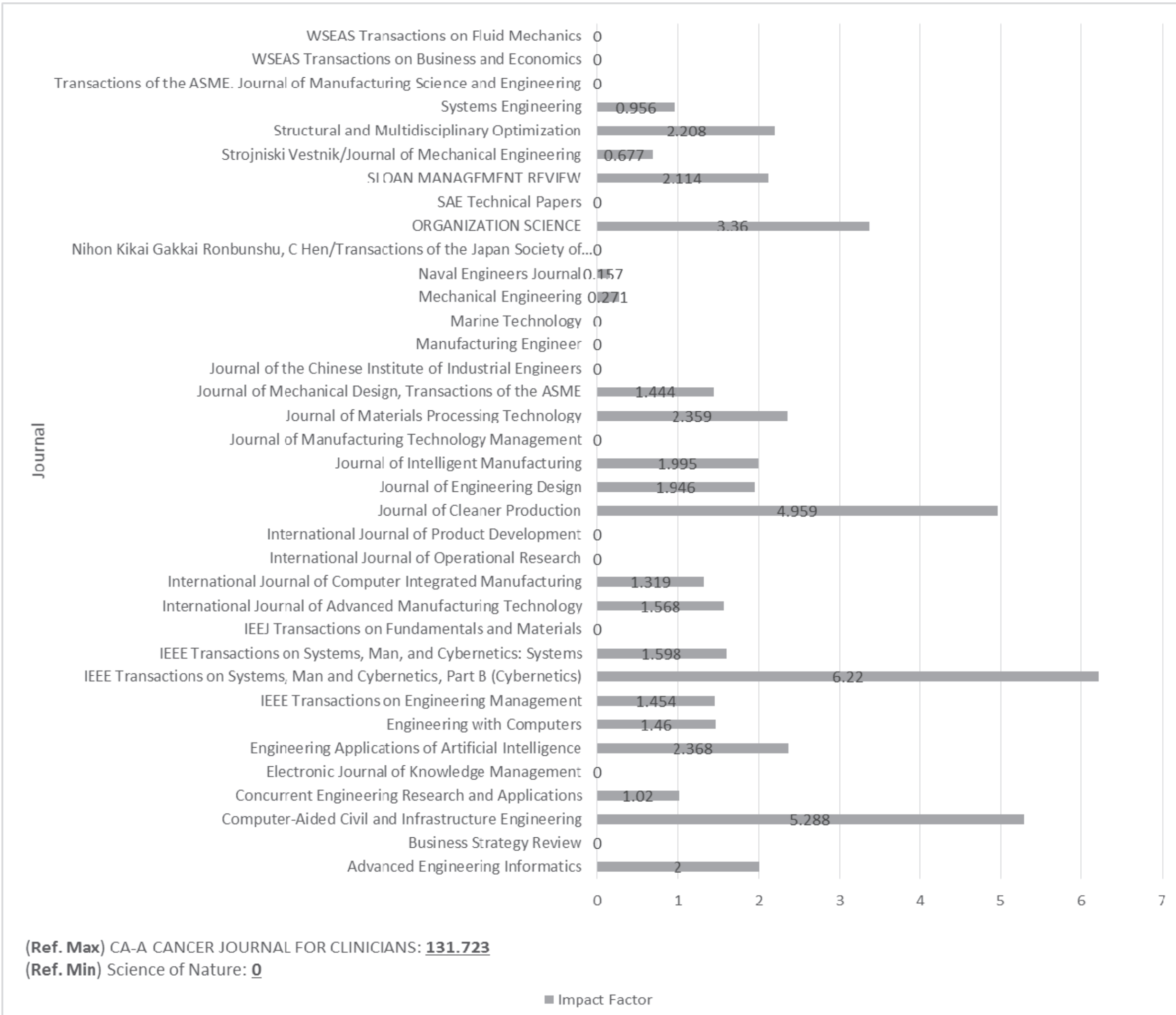


Figure 2.14: Category 1-5 journal Impact Factor (5-year Impact factor: 2010-2015)

The average Impact factor of the journals publishing the articles in the pool of SBCE relevant research works is relatively low. Concurrent Engineering Research and Applications, which is the journal with most (11) of the 61 journal publications, is however ranked 12th in the Computer, Database and Information Technology category. Sloan Management Review is ranked 11th in the Management, Business, Decision Science and Finance category, while IEEE Engineering Management Review is in the top 100 of the same category (81st). Another visible is the International Journal of Advanced Manufacturing Technology which is ranked 20th in the Mechanical, Production, Design, Automobile, Aeronautical and Industrial Engineering category. These findings suggest a larger breadth and interest in SBCE research as it extends across several influential journals in different domains. It is not possible to assess the depth of the research in each of these domains only by using the Impact Factor. Also, Impact factor is an indicator of how many citations an article receives on average when published in a journal (Fersht, 2009), which is in correlation with either the number of readers of the journal or the quality of the contents or both. It is not possible to distinguish the impact of SBCE publications as compared to other publications of the same journal when it comes to the journal Impact Factor. It is only possible to infer the potential visibility, importance and interest being given to the SBCE research. The Eigenfactor score similarly attempts to rate the influence of scientific journals by counting the number of citations a journal receives in a year and weighing them based on the importance of the journal with the incoming citation (Bergstrom, 2007). Eigenfactor score of journals that published the articles in the pool of SBCE relevant research works is shown below.

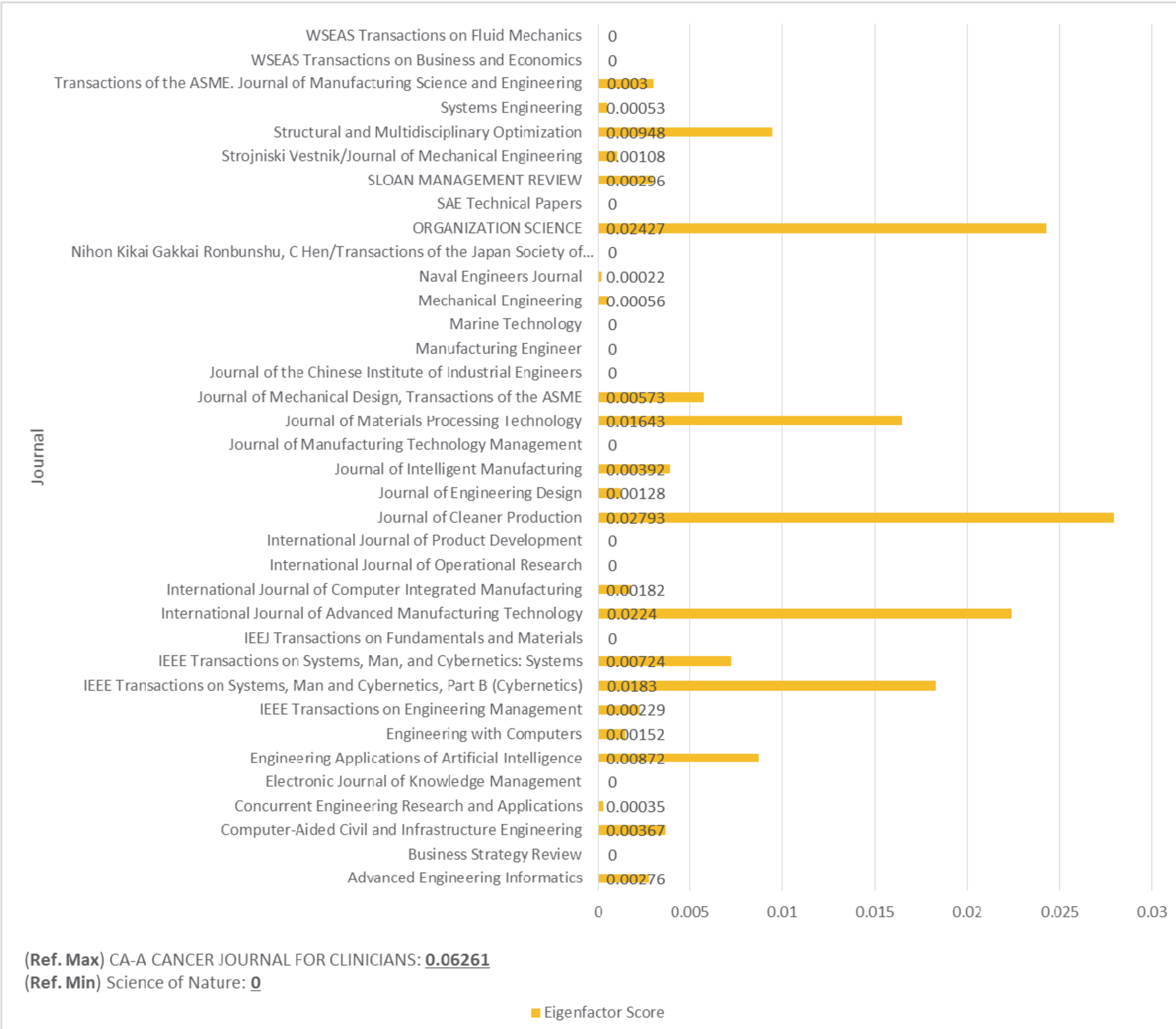


Figure 2.15: Category 1-5 journal Eigenfactor score

The results are very similar to Total Cites which is in line with the predicted strong correlation between Eigenfactors and the total number of citations received by a journal (Fersht, 2009). The same conclusions as for Total Cites above therefore apply.

2.2.3 Synthesis

This section continues on stage III of the systematic review protocol by discussing the most relevant research works (Category 5) into similar quantitative and furthermore in-depth qualitative details. As required by the systematic review guidelines, it was possible to divide the publications into a succession of epochs centered upon the formulation of the “second Toyota paradox" by Ward, Liker, Cristiano and Sobek (1995). Table 2.3 below lists the Cat-5 publications selected for review. These publications are examined by using the proposed dual analysis framework. The extended researcher's work (e.g. dissertation thesis) is additionally examined, when available, to support the overall synthesis and discussion.

Table 2.3: Category 5 SBCE publications

Author	Title	Year	Source
(Nahm & Ishikawa, 2006a)	A new 3D-CAD system for set-based parametric design	2006	International Journal of Advanced Manufacturing Technology
(Nahm & Ishikawa, 2006b)	Novel space-based design methodology for preliminary engineering design	2006	International Journal of Advanced Manufacturing Technology
(Sobek, 1996b)	Set-based model of design: the case of Toyota	1996	American Society of Mechanical Engineers (Paper)
(Sobek, 1996a)	Set-based model of design	1996	Mechanical Engineering
(Liker et al., 1996)	Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering	1996	IEEE Transactions on Engineering Management
(Ward et al., 1994)	Set-based concurrent engineering and Toyota	1994	American Society of Mechanical Engineers, Design Engineering Division (Publication) DE
(Al-Ashaab et al., 2016)	Development and application of lean product development performance measurement tool	2016	International Journal of Computer Integrated Manufacturing
(Levandowski, Müller, & Isaksson, 2016)	Modularization in concept development using functional modeling	2016	Advances in Transdisciplinary Engineering
(Raudberget, Michaelis, & Johannesson, 2014)	Combining set-based concurrent engineering and function-Means modelling to manage platform-based product family design	2014	IEEE International Conference on Industrial Engineering and Engineering Management
(Levandowski, Michaelis, & Johannesson, 2014a)	Set-based development using an integrated product and manufacturing system platform	2014	Concurrent Engineering Research and Applications
(Al-Ashaab et al., 2013)	The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry	2013	Concurrent Engineering Research and Applications
(Kerga, Taisch, & Terzi, 2013)	Set based concurrent engineering innovation roadmap	2013	IFIP Advances in Information and Communication Technology
(Michaelis, Levandowski, & Johannesson, 2013)	Set-based concurrent engineering for preserving design bandwidth in product and manufacturing system platforms	2013	ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)

Table 2.3 (Cont.): Category 5 SBCE publications

Author	Title	Year	Source
(Khan et al., 2011)	Set-based concurrent engineering process within the LeanPPD environment	2011	Advanced Concurrent Engineering
(Raudberget, 2011)	Enabling set-based concurrent engineering in traditional product development	2011	ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design
(Avigad & Moshaiov, 2009)	Set-based concept selection in multi-objective problems involving delayed decisions	2010	Journal of Engineering Design
(Inoue, Nahm, Okawa, & Ishikawa, 2010)	Design support system by combination of 3D-CAD and CAE with preference set-based design method	2010	Concurrent Engineering Research and Applications
(Shahan & Seepersad, 2010)	Implications of alternative multilevel design methods for design process management	2010	Concurrent Engineering Research and Applications
(Parrish, Wong, Tommelein, & Stojadinovic, 2008b)	Value propositions for set-based design of reinforced concrete structures	2008	Proceedings of IGLC16: 16th Annual Conference of the International Group for Lean Construction
(Levandowski, Forslund, Söderberg, & Johannesson, 2013)	Using PLM and trade-off curves to support set-based convergence of product platforms	2013	Proceedings of the International Conference on Engineering Design, ICED
(Araci, Al-Ashaab, & Maksimovic, 2016)	Knowledge Creation and Visualisation by Using Trade-off Curves to Enable Set-based Concurrent Engineering	2016	Electronic Journal of Knowledge Management
(Ghosh & Seering, 2014)	Set-based thinking in the engineering design community and beyond	2014	Proceedings of the ASME international design engineering technical conferences and computers and information in engineering conference, 2014
(Sobek et al., 1999)	Toyota's principles of set-based concurrent engineering	1999	Sloan management review
(Ward et al., 1995)	The 2nd Toyota paradox - how delaying decisions can make better cars faster	1995	Sloan management review

2.2.3.1 SBCE analysis (framework 1/2)

The chart below shows the distribution of the Cat-5 publications by segments of the proposed SBCE analysis framework.

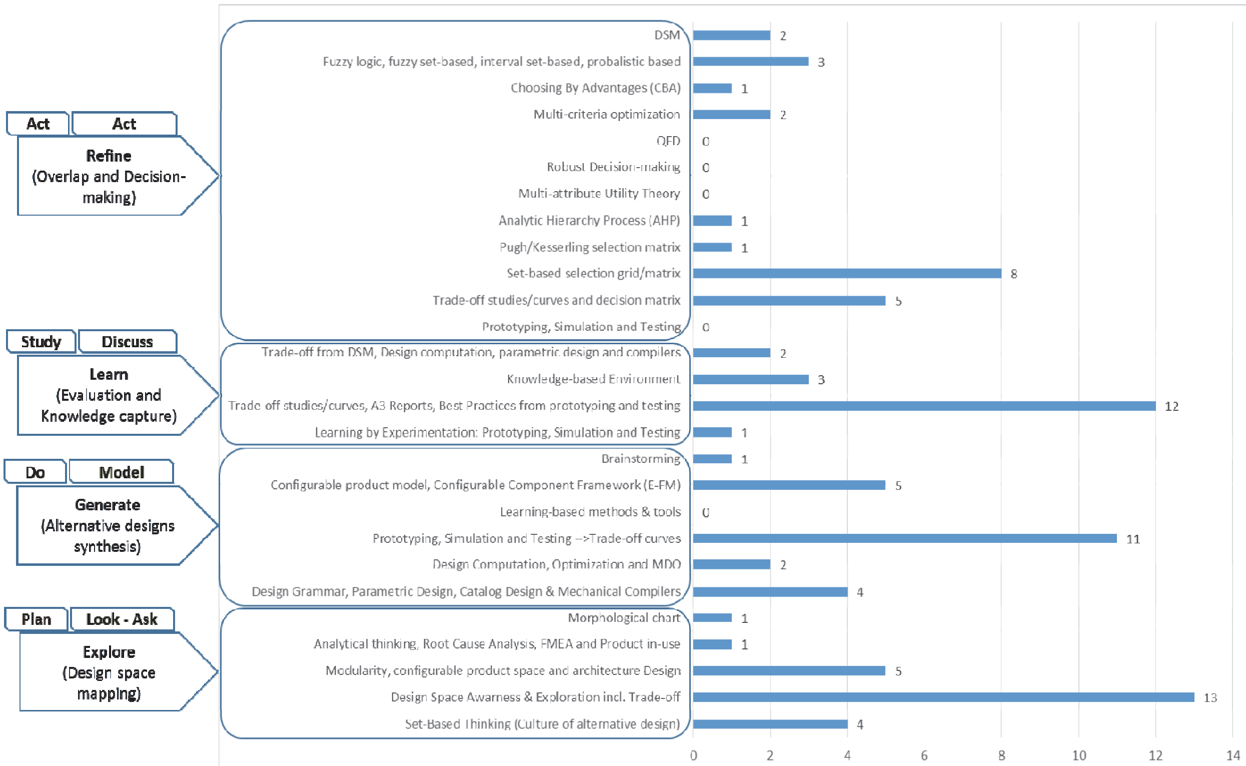


Figure 2.16: Distribution of the Cat-5 publications by SBCE analysis segments

The initial phase of the SBCE process is sometimes achieved by merely considering multiple alternatives long into the design process and without resorting to any specific technique. This SBCE culture of alternative designs exploration is a common practice in engineering design (Baxter, 1995; Cross, 1989; Hubka & Eder, 1987; Pahl & Beitz, 2013; Pugh, 1991; Ullman, 2009; Ulrich & Eppinger, 2012; Wheelwright & Clark, 1992) and it does not necessarily distinguishes SBCE from the other PD paradigms. In practice, it is the time and effort spent handling, exploring and documenting multiple alternatives long into the development process that makes SBCE different. Four of the 25 Cat-5 publications simply discuss this vision and practice during the PD process (Al-Ashaab et al., 2013; Al-Ashaab et al., 2016; Ghosh & Seering, 2014; Liker et al., 1996).

Design space awareness and exploration extends the vision by enabling the broad discovery of the design space to avoid narrowing too quickly on discrete areas of the space and thereby, losing the potential for innovation and discovery. Engineering design books and textbooks also advocate the practice using a variety of Knowledge-Based tools and techniques but there is a strong focus on trade-off studies and particularly trade-off curves within the SBCE literature (Araci et al., 2016; Maksimovic et al., 2012). This can be explained by a desire to explore and formalize Toyota's practice of SBCE as described by the foundational literature on SBCE (Sobek, 1996b; Sobek & Ward, 1996; Ward et al., 1994). The majority (≥60%) of the Cat-5 publications advocate exploring the design space, generating solutions and learning either by using computational tools (design grammars, parametric design, catalog design and mechanical compilers) (Avigad & Moshaiov, 2010; Inoue et al., 2010; Nahm & Ishikawa, 2006a, 2006b; Parrish et al., 2008b; Shahan & Seepersad, 2010) or developing trade-off curves through prototyping, simulation and testing during one or more of the three phases (Al-Ashaab et al., 2013; Al-Ashaab et al., 2016; Araci et al., 2016; Khan et al., 2011; Levandowski et al., 2013; Levandowski et al., 2014a; Liker et al., 1996; Michaelis et al., 2013; Raudberget, 2011; Sobek, 1996a, 1996b; Sobek et al., 1999; Ward et al., 1995; Ward et al., 1994).

From a product platform design standpoint, modularity, architecture design and the configurable product space (bandwidth) are also advocated within the SBCE literature as valid means to explore the design space and generate viable alternative designs (Levandowski et al., 2013; Levandowski et al., 2014a; Levandowski et al., 2016; Michaelis et al., 2013; Raudberget et al., 2014). The Configurable Component (CC) framework and Enhanced Function Means (E-FM) modelling by (Johannesson & Claesson, 2005) are used as the backbone to enable the approach during product platform design. Likewise, product structuring and configurable product models span multiple domains of the lifecycle (functional, technological, physical + process) and they are suitable for both product platform and single product (whatsoever) design/development (Andreasen, Hansen, & Mortensen, 1996; Erens, 1996; Huet, Fortin, McSorley, & Toche, 2011; Männistö et al., 2001; Toche et al., 2012; Wortmann & Erens, 1995), but they are rarely discussed in SBCE literature from a holistic PD perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework i.e. PDM/PLM.

The refinement phase of the SBCE process consists in overlapping alternative options from the disciplines and functional domains and making decisions to eliminate unfeasible designs. Overlapping the range options from many different views is generally perceived as complex and difficult to achieve and the researchers typically put forward trade-off studies, curves, generic decision matrices and the set-based selection grids and matrices for communicating and eliminating alternatives (Sobek et al., 1999). The matrices use technical and other qualitative aspects/criteria of a design from different domain perspectives to weight and assess the feasibility and performance of the design. Although Digital Mock-ups (DMU) and furthermore Functional DMU (FDMU) and industrial DMU (iDMU) extensively support the conventional industrial PDP (Drieux, 2006; Enge-Rosenblatt, Clauß, Schneider, & Schneider, 2011; Garbade & Dolezal, 2007; Herlem, Adragna, Ducellier, & Durupt, 2012; Lazzari & Raimondo, 2001; Mas et al., 2014), prototyping (virtual and physical) and testing (including simulations) are rarely used as actual means to enable the SBCE overlapping and decision-making process.

2.2.3.2 Research design analysis (framework 2/2)

The chart below displays the distribution of research paradigms and methods related to Cat-5 publications, which is the result of the assessment through the second layer of the proposed dual analysis framework.

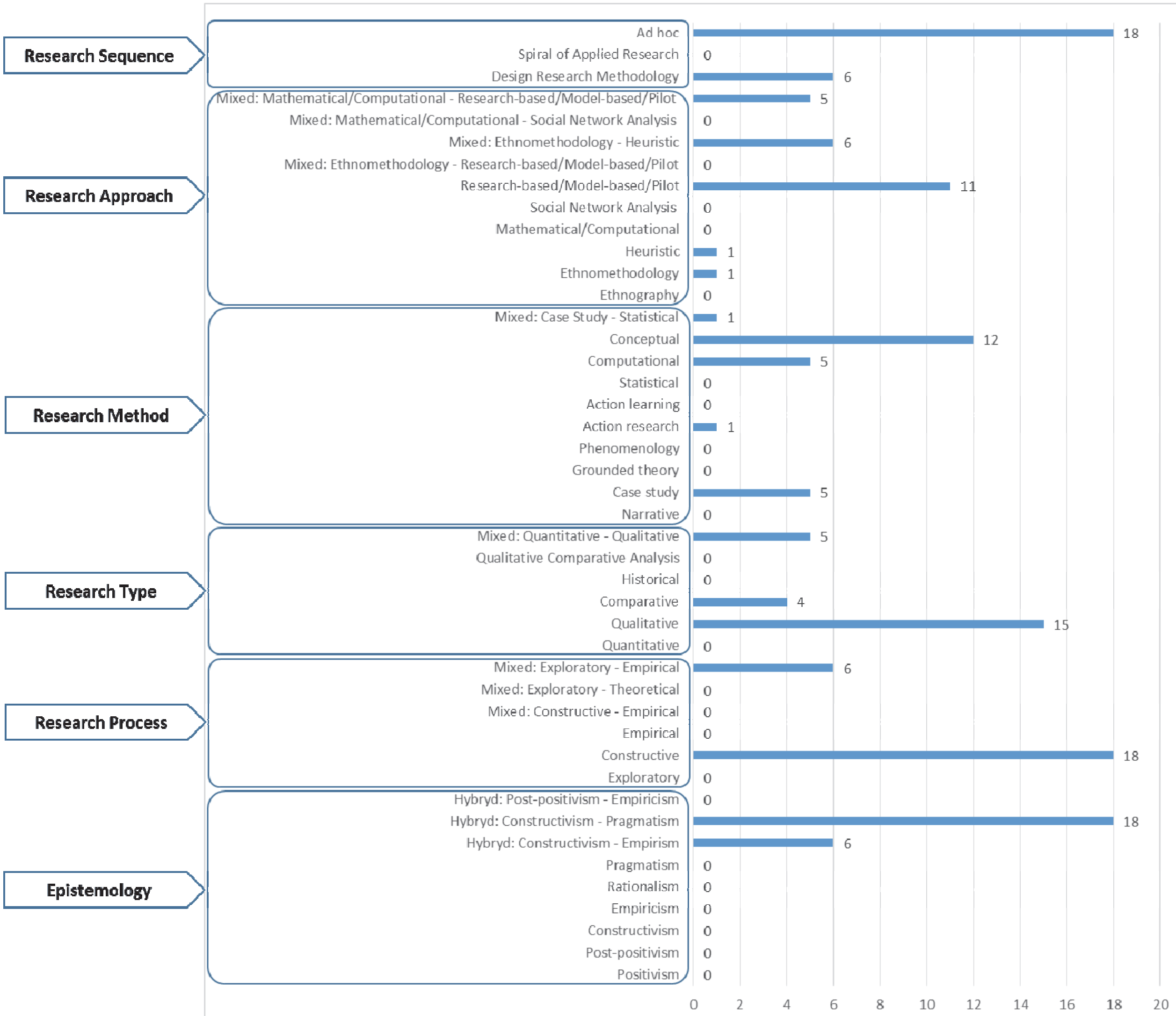


Figure 2.17: Distribution of the Cat-5 publications by Research paradigms and methods

The vast majority of SBCE research, when not explicit, suggests a constructivist-pragmatist stance (75%), which denotes a field in active construction with common ground assumptions, principles and philosophy, shared and accepted within the community and believed to be further theorized through reasoning, experience and research. Knowledge in the SCBE and LPPD community is viewed as a social construction (the community of SBCE and LPPD researchers) and the foundational theories and principles are consistently rooted to the same landmark research works, which, in this case, account for the rather constructivist-empiricist stance (25%) taken while studying Toyota and the Japanese automakers.

SBCE research is marked by inquiries into the interdisciplinary interactions within the design and product development process while discovering and understanding the enablers and catalysts of the practice of SBCE in context-specific settings. SBCE research is therefore predominantly qualitative, inductive, proceeding through natural inquiries. Data is expressed in the form of words rather than numbers but quantitative analysis is often used to either support experimental and computational methods, determine causality or to simply make sense of the data in order to generalize findings and extrapolate to similar situations. Qualitative coding (Strauss & Corbin, 1990) is frequently used to segment the data into categories that facilitate in-depth understanding, comparison and the development of the SBCE theory. Comparative research is applicable to the foundational research works that formulated the SBCE concepts through the benchmarking, study and comparison of the world automakers. These researchers mainly performed case studies, which allowed them to understand the "How" and "Why" from the natural settings of actual SBCE practitioners. The remaining research works are theoretical, conceptual and computational by nature, proceeding through research-based, model-based and pilot research to either generate a theory of SBCE or improve, confirm one constructed so far. There is one action research performed in civil engineering (construction industry), which also account for the one purely ethnomethodology approach reported in the chart. The benchmarking and comparative studies performed by the foundational research works is, by contrast, regarded as mixing ethnomethodology and heuristic. From a research sequence standpoint, the larger part of the SBCE research (75%) follows ad hoc sequences with respect to the scientific method. The remaining part displays a preference for the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009).

The next sections discuss Cat-5 publications into more details, while following a succession of epochs which are centered upon the formulation of the "second Toyota paradox" by Ward, Liker, Cristiano and Sobek (1995).

2.2.3.3 Before the second Toyota paradox

As discussed in section 2.2.2.3, set-based reasoning and methods existed close before the "second Toyota paradox". These early 90's research on engineering design calculations involved set-based reasoning by using fuzzy parameters, labeled interval calculus and other methods like the Method of Imprecision (MoI) and constraint satisfaction (Antonsson & Wood, 1989; ElMaraghy & Jack, 1993; Hernandez-Luna & Wood, 1994; Hyvönen, 1992; Tommelein, 1989; Ward, 1989; Wood et al., 1992). However, they did not entail the holistic SBCE philosophy and principles and the institutional knowledge capture and reuse advocated to enable a superior PD process as exemplified in the "second Toyota paradox" (Ward et al., 1995). In addition, these early research works involving set-based methods were not always nominally identified as such, which is the reason why some are retrieved by the keywords search and some other are not. The complimentary publications are discussed here as discovered through the references backtracking and with the sole purpose of understanding what set-based thinking was about before the "second Toyota paradox". For instance, Ward initially developed a theory of quantitative inference for artefact sets applied to design compilers, in particular, mechanical design compilers. The software construct used a schematic and high level labelled interval specification language to allow a mechanical designer to search for an optimal design through a component database. The search then returned appropriate catalogue numbers of the granular components and progressively narrowed them until an overall cost function was fulfilled. The theory and the resulting software implementation represented and manipulated sets of artefacts and operating conditions rather than a single artefact under a single operating condition. Moreover, it performed searches by progressively narrowing volumes of the artefact space rather than searching point to point in that space. The theory and its implementation echoes with set-based design as it was later formulated by the author. Another example of set-based reasoning applied to a design process before the "second Toyota paradox" is the work done by Tommelein in structural engineering. Tommelein (1989) used a set-based methodology to generate adequate construction site layouts by reasoning about spatial constraints that need to be satisfied between rectangular sets in a layout. The approach was implemented in a software called SightPlan which is based upon the Blackboard (BB1) architecture for combining geometry under constraints and displaying emerging solutions without committing to a specific one (Tommelein, 1989). From a similar perspective, Antonnsson and Wood stress uncertainty and the fuzzy nature of specifications and requirements during the design by formulating the design problem in terms of fuzzy parameters and constraints. They generate a range of possible design variable values (fuzzy sets of designs) using their fuzzy sets Method of Imprecision (MoI). This method resolves the design variable values by mapping the design preference onto the performance space while also quantifying imprecision (Antonsson & Wood, 1989; Hernandez-Luna & Wood, 1994; Wood et al., 1992). Other methods preceding the "second Toyota paradox" include, but are not limited to, the use of Boolean equations (ElMaraghy & Jack, 1993) and interval arithmetic (Hyvönen, 1992) to resolve design problems and especially communicate between disciplines (e.g. design - manufacturing) by range of parameter values rather than a single value at a time.

2.2.3.4 The second Toyota paradox

Set-based concurrent engineering, as it refers to Toyota's practice, was coined by Ward et al. (1994) in their landmark paper presented at the proceedings of the 1994 ASME Design Technical Conferences in Minneapolis, USA. The paper presents a new paradigm for concurrent or simultaneous design. The paradigm is about apparent paradoxes in Toyota Motor Company's new product development strategies. Evidences from various interviews in the U.S. and Japanese automakers and automotive parts suppliers are presented, including two in-depth case studies. The paper concludes with a discussion of the potential benefits of this paradigm. The paradigm is then extended in an article published the following year in the MIT Sloan Management Review (Ward et al., 1995). According to the authors, the first Toyota paradox is Toyota's lean production system as already discussed here involving unusual practices from a traditional mass production perspective (see section 2.1.1). The article introduces the reader to the second Toyota paradox which is basically the set-based concurrent engineering (SBCE) paradigm. The paradox is expressed by means of delaying decisions, communicating about range of possibilities and pursuing excessive numbers of prototypes. These together form the way by which Toyota is believed to design better cars faster and cheaper. The authors explain that in their practice of SBCE, Toyota's engineers "intuitively" distinguish between cases requiring broad design space exploration as opposed to cases where a narrow, more constrained search is suitable (Ward and Sobek (2014) later formally described how to make this determination based upon the type of development project on hand, see Table 4.1). The SBCE characteristics, techniques and advantages are explained emphasizing a process that relies on handling and narrowing sets of possible solutions through design space exploration, prototyping, learning and commitment to robustness, all this by using effective management practices and the chief engineer concept. Many detailed examples of SBCE interactions among Toyota's functional disciplines are discussed on one side and, Toyota's SBCE interactions with its suppliers on the other side, this by deep diving into Nippodenso's exemplary practice of SBCE. The authors conclude with the prediction that "companies adopting concurrent engineering through cross-functional teams and structured development process that focus on designing the right product in the concept stage will inevitably move in the direction of set-based concurrent engineering" (Ward et al., 1995).

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

In search of evidences for set-based concurrent engineering, Liker et al. investigated 92 Japanese and 119 US. automotive parts suppliers, with the purpose of determining the prevalence of set-based approaches in each group based upon predefined indicators (Liker et al., 1996). The outcome of the survey evidenced that set-based design communication was more prevalent among Japanese suppliers than among their US. counterpart. Set-based CE is contrasted in the article with traditional CE, emphasizing the need for a paradigm shift in order to operate an effective, truly concurrent engineering. Set-based CE paradigm is discussed in details, explaining the difference with traditional CE when it comes to communicating requirements, exploring the solution space and communicating about designs (product or manufacturing process) by using ranges, gradually narrowing ranges, using parallel approaches, large numbers of prototypes and by exploring trade-offs. The effect of supplier's involvement early in the design process and the correlation with the use of set-based techniques is explored, concluding on a strong positive correlation. Another correlation that is explored is the relationship between the use of set-based techniques and the degree to which product-process design overlaps, which surprisingly concludes on a weak association. Component interdependence and the use of Quality Function

Deployment (QFD) are also considered set-based indicators and they are equally explored in relation to the practice of set-based CE among the groups. The 2 indicators display strong associations with set-based design practices. The authors believe that set-based design philosophy has the potential to "provide high-bandwidth, trustworthy, and useful information creation and transmission". As such, these authors stress important implications of set-based CE which include: (1) going slow early in the process and developing large numbers of alternatives that allow for faster downstream design with less rework cycles; (2) developing new vocabularies for participants to communicate in sets; (3) switching organisational mindset to think in terms of narrowing sets rather than iterating on one single solution; (4) reconsidering the usage of CAD systems early in the design process as they force commitment to many specific design decisions and finally; (5) potentially reducing the need for frequent face-to-face communication. Additional research is recommended by the authors to more carefully develop indicators and metrics for point-based versus set-based design. The authors highlight the fact that the list of set-based indicators used in the survey is not exhaustive and that it should not be considered perfect neither. According to the same authors, theories, principles and basically what makes a CE set-based should be better studied and formalised in order to perform accurate measures of the set-basedness of an organisation.

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

In essence, the authors that participated in formulating the second Toyota paradox collectively recommend further study of the causal relationship between Toyota's success and its practice of SBCE as evidenced and synthesized. The authors acknowledge that SBCE as described is the result of their perception of a system that is not explicitly documented or known to be well understood and performed in a systematic way. They therefore prompt researchers to construct the methodologies of SBCE and test them in other organisations in order to formulate a complete theory of set-based design.

2.2.3.5 After the second Toyota paradox

As a way to follow upon the SBCE landmark research recommendations, the post-second-Toyota-paradox research works are usually performed outside the context of Toyota or any SBCE-proven Japanese entity, but at the same time, by quite systematically leveraging the philosophy, theories and principles developed while formulating the second Toyota paradox. This is to say, the SBCE philosophy, theories and principles as discussed above are collectively accepted, not reconsidered but rather studied and implemented in a constructivist-pragmatist way in order to confirm the premises or formulate a more complete theory of set-based design. For example, although Liker et al. indicated that the use of CAD systems early in the design process should be reconsidered as they force commitment to many specific design decisions, Nahm, Ishikiwa and Inoue leverage advances in CAD systems to propose a CAD oriented set based design methodology that can support preliminary design activities and decisions (Inoue et al., 2010; Nahm & Ishikawa, 2006a, 2006b). Indeed, the authors research work is motivated by the limitations of the traditional CAD systems in: (1) supporting the conceptual design stage with its design information scarceness and uncertainty and; (2) handling non-geometrical information which are complementary and necessary design information required to fully define an engineering artefact as well as furthermore linking the CAD systems with other engineering systems and CE processes. These authors research is geared to provide a blend of methods and tools characterized by a parametric communication and robust design convergence process using uncertain and incomplete information in support to the set-based design paradigm. Their work combines set-based design with the parametric modelling technique, now deployed in the geometric modelling kernels of most of the CAD systems. The combination produces a new concept called set-based parametric design (SBPD) for which a preference set-based design (PSD) model and a design information solid (DIS) model are proposed to ease the incorporation of the SBPD concept into the current CAD systems. Simply put, the DIS model augments the CAD data structure by adding non-geometrical design information as attribute data of the Boundary representation (B-Reps) of the solid models (Nahm & Ishikawa, 2006a). It then becomes possible to store qualitative information such as functions, design intent, applicability, materials, context domain information e.g. assemblability data, search index strings, etc. A designer working with a parametric solid model may populate the geometrical and non-geometrical parameter data and constraints which will later be scanned by the PSD model when exploring the design space. The PSD model is a set-to-set mapping that propagates a designer preference sets (input) onto the available rich parametric solid models, given the constraints, so as to explore the interval sets and produce outputs under design information uncertainty (Nahm & Ishikawa, 2006a). PSD is a hybrid model that combines Antonnsson and Wood (1989) fuzzy set-based method of imprecision (MoI) with Finch and Ward (1997) interval set-based approach (which in turn is made up of the Quantified Relations (QRs) and the interval propagation theorem (IPT) algorithm). For instance, Nahm and Ishikawa presents a prototype system implementation using the PARASOLID CAD kernel to both illustrate the feasibility of the DIS model as well as the robustness of a PSD processor while propagating, aggregating, modifying and narrowing interval sets in order to infer solution sets (Nahm & Ishikawa, 2006a). Nahm, Ishikiwa and Inoue research work is essentially motivated by the need to develop space representation methods, space mapping methods and space narrowing methods in support to effective implementation of SBCE. These authors discuss a new space-oriented design methodology which is based upon interval sets and preference functions defined on the sets. The approaches used for processing the intervals include decomposed fuzzy arithmetic, extended interval arithmetic i.e. IPT, Design of Experiment (DoE) and a new design metric called preference and robustness index (PRI). The combination of the approaches and metrics allows for a set-to-set mapping from a design space to a performance space and subsequent narrowing of the interval sets to eliminate unfeasible sub-space solutions (Inoue et al., 2010; Nahm & Ishikawa, 2006a, 2006b). Following their research, Nahm and Ishikawa recommend that future research should pay more attention to the data-level, interface-level, and application-level integration of heterogeneous 3D-CAD systems as well as the collaboration/interoperability required between CAx tools (Nahm & Ishikawa, 2006a). Some limitations regarding the proposed PSD model are also highlighted which mainly consist in the inability of the model to produce correct output intervals for some combinations of input intervals. The limitation is thought to be caused by the direct use of IPT. Further research is prompted to allow checking the "reasonableness" of an input sets in order to avoid the designer's trial-and-error procedure that may become painful while searching for a correct input interval using the proposed implementation.

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

Drawing upon previous groundwork, Al-Ashab et al. discuss the development of a lean product development performance measurement tool to assess the "leaness" of a PD process. By recognizing that SBCE is the core component of LPPD, the authors devise a two prong assessment tool that relies on the enablers of their leanPPD model as well as the principles of SBCE synthesised from the existing literature by (Khan et al., 2011; Khan et al., 2013). The tool assess a company's practice of SBCE and LPPD from 4 perspectives (Al-Ashaab et al., 2016): (1) product development process i.e. directly referring to the practice of SBCE and the presence of the chief engineer and value focus enablers; (2) tools and enablers as collected by Khan et al. regarding lean and SBCE; (3) knowledge focus which is key to lean i.e. Knowledge-Based environment to support the capture, storage, retrieval, communication and the institutional learning as advocated by Ward and Sobek (2014), and finally; (4) continuous improvement as a mean for the tool to both express the as-is state and furthermore drive to an implementation roadmap. The authors propose an assessment scale called SAUCE (Start-Awareness-Unstructured-Continued-Evolved) to allow a visual representation of a company's current "leaness" state as well as to become an incentive to devise the improvement plan towards the next level. The scale, by its non-cyclic nature cannot be considered a continuous improvement tool per se (with reference to PDSA, DMAIC, LAMDA etc.) but rather a tool to support improvement towards a fixed, desired state. Regardless, intended assessments are performed in one aerospace company and one automotive company to demonstrate the ability of the measurement tool and the SAUCE scale to systematically provide insights into these companies practice of lean PD and SBCE. Indeed, the research have effectively developped on a tool to assess the lean PD and SBCE practice of a company based upon enablers in the LeanPPD model as well as principles of SBCE as synthesized from the literature. The research however does not discuss approaches, methodologies or frameworks that can actually support the lean transformation within an organisation. This is seen as future research opportunities by the authors. Other works by the same authors focus on specific SBCE key enablers by attempting to develop upon such techniques and practices. For example, Araci, al-Ashab and Maksimovic (2016) concentrate on the use of Trade-off curves (ToC) to enable SBCE and LPPD, by proposing a process for generating and leveraging knowledge-based and math-based ToCs at each stage of the "set-based concurrent engineering baseline model" described by Khan (2012). While these authors deepen understanding and applicability of a well-known SBCE enabler (Sobek et al., 1999; Ward & Sobek, 2014), they rely on the SBCE baseline model that has previously been criticised for its point-basedness (Raudberget, 2015) p.26. In addition, the means by which sets of designs are composed, overlapped, narrowed and eliminated using different functional groups ToCs is unclear. Maulana et al. (2016) potentially fill this gap in their application of SBCE to enhance the design performance of a surface jet pump. These authors first develop concept sets using ToCs, stakeholder's expertise and brainstorming. Then they eliminate unfeasible sets by using the Analytical Hierarchy Process (AHP) (Saaty, 1990) fed by data gathered from prototyping and testing i.e. CFD simulations and past project data. Al-ashab et al. (2013) also use AHP in the same vein. They describe a transformation process towards lean product development in a company. The transformation consists of 2 stages whereby the first integrates principles of SBCE, as synthesised from the existing literature (Khan et al., 2013), into an existing product development process by timely introducing the relevant lean activities and tools e.g. QFD, Brainstorming, DoE, Pugh matrix, AHP, FMEA, risk analysis, etc. The second stage infers a generic model of the structured activities and tools for the corresponding type of transformation into lean PD, which is then applied to a research-based case study. Although their research work can be seen as specific to a particular development context, it however provides some guidelines on how to restructure existing PD activities and appropriately use SBCE principles and tools to transition the PD to a lean PD. This again is a blend of activities, tools and techniques that forms an approach or so-called SBCE process which do not rely on a proven SBCE model and especially one leveraging any proven design process model, product model or Knowledge-Based model which can holistically and systematically federate the 3Ps (People-Product-Process) towards SBCE and LPPD in such industrial context.

A potentially advanced model and SBCE practical approach can be found in the research work done at the Department of Product and Production Development, Chalmers University of Technology in Sweden (Levandowski, 2014; Michaelis et al., 2013; Raudberget, 2015). These authors leverage the Configurable Component (CC) framework and Enhanced Function Means (E-FM) modelling by (Johannesson & Claesson, 2005) to enable SBCE during product platform design. The related manufacturing process design is also considered. Configurability is perceived and advocated as a fundamental mean to handle multiple design alternatives, allow for mapping, exploring the design space and gradually narrowing sets while preserving the design bandwidth i.e. decision delay. The design bandwidth concept is equivalent to the viable, flexible solution sets that represent architectural options from which a coherent product design can be extracted, instantiated and passed onto downstream processes for further design and validation (Berglund & Claesson, 2005). E-FM modelling presents the advantage of spanning the functional (FRs) and technological/physical (DSs) domains, which allows for variability both at the functional requirement level and the logical system design level i.e. functional feature. It is not always easy to understand the difference and interaction between the CC framework and E-FM modelling. The CC framework is essentially a mean to encapsulate a system level design variability and thereby, bridge the gap between the technological domain (DSs) and the physical domain (Parts) where applicable. To achieve this, the CC framework is built upon configuration rules for Part selection from catalogs which allows to extend variability in the technological and functional domains down to variability in the physical domain in order to translate architectural options into various workable product variants. Fig. 2.18 illustrates the E-FM tree model and the interaction with the CC framework.

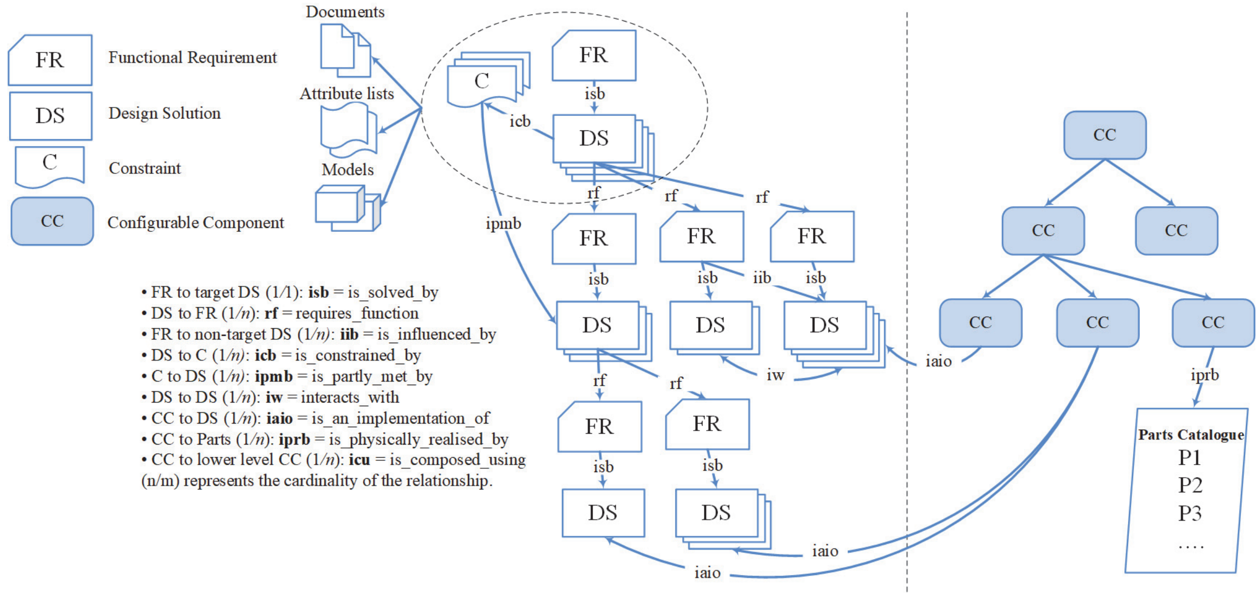


Figure 2.18: Enhanced Function Means (E-FM) and Configurable Component (CC) framework. Adapted from (Johannesson & Claesson, 2005).

An instantiation input (design parameters) is usually passed to the CC framework which may then extract a specific physical design variant based upon the system level architecture it has inherited from the E-FM tree (Johannesson & Claesson, 2005). Johannesson and Claesson mention that the information technology necessary to support the discussed framework is commercially available in Product Data Management (PDM) systems such as iMAN from EDS PLM Solutions which is now part of the Siemens PLM software i.e. Teamcenter. The E-FM and CC framework will be further discussed in chapter 5 (see section 5.2) as they both show core similarities with product models usually deployed in industrial PLM software and furthermore, demonstrate strong compatibility with SBCE. Michaelis, Lewandowski and Raudberget basically leverage the combinatorial effects of variability and configurability within the E-FM and CC framework to advocate the strong compatibility with SBCE design space exploration. These authors use variability within the E-FM tree model to handle multiple architectural options that can then be analysed with the purpose of reducing functional, design solutions couplings (*interacts_with* and *is_influenced_by* relationships) and furthermore, progressively eliminating unfeasible designs at the conceptual level (Levandowski, 2014; Michaelis et al., 2013; Raudberget, 2015). This is also seen as extendable to manufacturing processes (Johannesson & Claesson, 2005; Levandowski et al., 2014a). The framework allows for SBCE convergence processes because it supports: (1) exploration of a product platform design space as well as elimination of unfeasible designs and; (2) preservation of conceptual solution sets until variants are instantiated though the CC framework for embodiment design and reality check. Although the framework evidently shows capabilities at the conceptual level, it remains unclear how the functional groups i.e. requirements engineering, advance engineering, systems engineering, components engineering, etc. may interact using it. To cite Johannesson and Claesson (2005), the corresponding development approach i.e. end-to-end life cycle, that relates to the framework and fully exploits it remains unclear. The life cycle stages beyond conceptual design are rarely addressed which results in a void when it comes to SBCE front-loading process, reusable design knowledge management, prototyping and testing for an informed convergence process, value streams cross functional interactions and basically the remaining SBCE means by which a product platform or single product can be developed in a large-scale industry conventional PD framework and lean context. Lewandowski et al. (2013) attempt to fill these gaps by exploring an approach by which product variants are instantiated from the CC modeller and then passed to a PLM software to engage downstream activities in the development process. Virtual prototyping and simulations are performed through the normal PLM process, then trade-off curves are produced to inform the E-FM/CC platform design by means of analog feedback, which then helps the product platform design convergence process. This approach discloses dislocated methodologies and tools that promote scatter, hand-offs and waste. The same approach and resulting gaps remain present in these authors latest publication i.e. (Johannesson et al., 2017) as acquired through the systematic review monitoring process following the first round dual framework analysis reported in this section. It is argued in this thesis that product modelling and configurable product models span multiple domains of the lifecycle i.e. functional, technological, physical, process (Andreasen et al., 1996; Erens, 1996; Huet et al., 2011; Männistö et al., 2001; Toche et al., 2012; Wortmann & Erens, 1995) and their ability to enable SBCE can be explored from a holistic PD perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework i.e. PDM/PLM. This will be elaborated in chapter 5.

Other significant post-second-Toyota-paradox research include the works done by Parrish et al., Kerga, Taisch and Terzi, Avigad and Moshaiov as well as Shahan and Seepersad. Parrish et al. explored the benefits of implementing SBCE during the design of reinforced concrete structures (Parrish, 2009; Parrish et al., 2008a). Variability is considered and alternative design solutions are explored using Building Information Modelling (BIM) software, which is similar to PLM software in many aspects (Jupp, 2016). Parrish (2009) emphasizes stakeholders interaction while communicating, postponing and deciding about sets of design. This author proposes a comprehensive comparative study of a variety of decision-making processes/methods ranging from Robust Decision-making (Ullman, 2001), Multi-attribute Utility Theory (Thurston, 1990), Analytic Hierarchy Process (AHP) (Saaty, 1990) to Choosing By Advantages (CBA) (Suhr, 1999), to name a few. Parrish in her dissertation thesis states that "literature cannot prescribe a set of steps to implement a set-based design process, since it is context-specific. It varies with the stakeholders involved, the design phase, the decision unit, and the project itself" (Parrish, 2009) p.266. A manifestation of this can be found in (Kerga et al., 2014a) where trade-off curves are perceived as detrimental to the set-based innovation process. The theory of inventive problem solving (TRIZ) by Altshuller (1984) is forwarded as an improved methodological approach while implementing SBCE. This superiority compared to trade-off curves within the set-based innovation process is supported by little theoretical grounds and therefore requires more substance. From a different perspective, Avigad and Moshaiov propose an approach to delay conceptual decisions under uncertainty while maintaining and assessing the performance of multiple design concepts. This is done by translating the design problem into a multi-objective problem and by mapping each of the design concepts to a cluster of points in the objective space, representing the discrete options performances (Avigad & Moshaiov, 2010). The approach requires abstracting the design problem into a design space tree i.e. *Complete Concept* tree and furthermore, an objective and variability space. The authors argue that when achieved properly, the approach may allow to compare design concepts based on their robustness i.e. sensitivity to change according to the delayed decisions uncertainty. This approach is evidently relevant to SBCE during preliminary conceptual work but it requires several levels of abstraction and computation that may not be compatible with practical, industrial SBCE endeavours. The SBCE Knowledge-Based process is also unclear. The remaining part of the post-second-Toyota-paradox research usually consists of confirmatory studies of SBCE performance using computational simulations or pilot projects. For example, Shahan and Seepersad (2010) use multi-criteria optimization and discrete event simulations to explore the effects of highly iterative exchanges of single design solutions (point-based) vs. minimally iterative exchanges of multiple solutions (set-based) on the overall lead time of a design process. These authors conclude in favor of the reduced overall iteration cycles (hence shorter lead times) as well as the robust convergence in the case of flexible, optimal size, rich and less frequent exchanges of information. These findings are similar to (Beauregard et al., 2014) and they are consistent with the findings by (Ford & Sobek, 2005) with regards to their assessment of the development project performance in set-based vs. point-based using real options valuation models. Shahan and Seepersad (2010) in conclusions mention that their simulations were done on serialized processes. They note the necessity for the research to investigate concurrent execution of these design processes in the context of computer-aided engineering (CAx) tools with product lifecycle management (PLM) and Knowledge-Based engineering capabilities.

2.3 Conclusion

A review of lean, PD, and LPD literature was first presented in this chapter by discussing the concepts, theoretical grounds, practical implications and advances in the fields. Recent studies on lean PD in aerospace industry showed that the maturity of lean PD implementation in the industry is low, no more than at introductory level and it has not been possible so far to find a company that coherently combines the LPD enablers into a whole to improve its PD process in a lean way (Al-Ashaab et al., 2016; Beauregard et al., 2014; McManus et al., 2005; Rebentisch, 2008). The review of the literature showed that LPD research has focused on the principles and concepts underlying LPD i.e. what should be done, the tools and techniques to implement the approach, rather than converging to a mature theory/model (conceptual focus and theory-building) and the methodologies for the implementation, tool integration, coordination strategies, performance measures and causality effect assessments (Hoppmann et al., 2011; León & Farris, 2011). It is also pointed that the models and methodologies should show compatibility with conventional PD asset and deployed technology in order to avoid disruption but rather stay within the bandwidth of long-term investments while positively balancing the burden of their implementation (Khan, 2012; León & Farris, 2011). Set-based Engineering, set-based design or SBCE (the practice of set-based design) has emerged as a strong component of lean PD with all authors describing it as the core enabler of LPD. A systematic review of SBCE was carried in this chapter for this reason and, because it is the main focus of the present dissertation. This systematic review followed an evidence-based procedure (NHS, 2001; Tranfield et al., 2003) to analyse the SBCE literature using a newly devised dual analysis framework i.e. approach to the Design process on one hand and, Research paradigm on the other hand. The review question, according to the evidence-based systematic review procedure requirements, was to discover and analyse the SBCE literature characteristics, enablers and catalysts for proposing/developing holistic models and methodologies intended to support the transition to SBCE from the current PD practice, conventional tools and assets. The final stage of the procedure consisted in a synthesis from which the research opportunities pertaining to this thesis are summarized below:

- Research is required to extend the application of SBCE theories and principles beyond the conceptual design stage, especially implications for detailed design, prototyping, testing and the rest of the product lifecycle;
- SBCE research authors consistently agree on the lack of holistic models that can support the cross-domain communication, overlapping, narrowing, and refinement of sets and, furthermore, enable the iterative institutional learning capability which is core to SBCE and lean PD. This gap is currently not filled;
- Product structuring, configurability and variability emerged as practical SBCE enablers but they remain scarce within the SBCE literature. Their ability to enable SBCE is not explored from a holistic PD, lifecycle perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework i.e. PDM/PLM;
- Although the literature regularly stipulates that extensive prototyping and testing is key to SBCE in order to foster the Knowledge-Based environment, institutional learning capability and to inform the decision-making process, prototyping (virtual and physical) and testing (incl. simulations) frameworks and activities are rarely addressed within the SBCE literature;
- The effects of major SBCE enablers e.g. product structuring, configurability, prototyping, set-based selection process etc. on the development process performance

are rarely studied, whether by experimenting alternative hypothesis or disproving null hypothesis.

Two contributions from this research that can readily be mentioned are: (1) the proposal of a new SBCE dual analysis framework combined with an evidence-based systematic review methodology and; (2) the advancement of theoretical and practical understanding of LPD and SBCE from the larger to the most significant aspects.

CHAPTER 3 METHODOLOGY

A systematic review of SBCE was performed in the previous chapter in order to understand the theoretical and conceptual grounds of the field, understand the research contributions into the field, their implications and finally, delimit areas requiring further research according to the research objective. The current chapter first describes the research hypotheses as they relate to the research opportunities and the completion of the objective. The chapter then discusses Design science, research paradigms and methodological frameworks in the perspective of the thesis work. The research approach is presented detailing the selected appropriate type of research, method(s) and implementation stages with regards to the research project. The thesis structure is finally laid out in relation to the chosen overarching research methodology.

3.1 Research questions and objectives

As introduced earlier, this research is motivated by the necessity to develop understanding and support for practical implementations of lean product development and especially Set-Based Concurrent Engineering (SBCE) in industry. Such necessity is justified by 21st century compelling socioeconomic factors that demand robust, resilient, responsive, flexible, innovative, adaptable and lean product development processes in order for companies to stay competitive in rapidly changing markets.

The main objective of the research is therefore to identify and develop the most essential SBCE-related ingredients of the aerospace industrial product development framework in order to form a holistic model that can support practical implementations of SBCE and LPD from a product lifecycle perspective. This objective can be met by answering the following questions:

RQ1. What aspects, characteristics and features of the aerospace industrial product development are catalysts of a potential transition to SBCE and LPD?

RQ2. What is an appropriate approach for various domains of expertise within the aerospace industrial product development to exchange on the basis of alternative design solutions and furthermore, narrow down to an optimal design by following a set-based convergence process?

RQ3. Does a holistic model exist or can it be developed to support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective?

The LPD comprehensive review and SBCE systematic review performed in chapter 2 have touched upon the three questions, providing rationale and evidences that contribute to partially answer the questions and better orient the research. SBCE enablers, practices, tools and techniques as synthesized into a framework to analyse the literature can be regarded as the collected catalysts from which the most essential have been examined. These should be brought together into a cohesive whole, studied and validated with the purpose of forming the bespoken holistic model. Indeed, the systematic review has evidenced that the maturity of lean PD implementation in the aerospace industry is low, no more than at introductory level and it has not been possible so far to find a company that coherently combines the LPD/SBCE enablers into a whole to improve its PD process in a lean way (Al-Ashaab et al., 2016; Beauregard et al., 2014; McManus et al., 2005; Rebentisch, 2008). Based on this finding, the identified SBCE key catalysts (e.g. product structuring, configurability, prototyping, set-based selection process, etc.) and the research opportunities distilled through the systematic review, it is hypothesized that:

$H1_1$: A product structuring model that supports concurrent engineering on one hand and, the configurable virtual product synchronized with prototyping as-tested structures on the other hand, can provide effective means to enable an enterprise level SBCE that spans the product lifecycle;

$H2_1$: Virtual prototyping tuned by physical prototyping and, combined with a set-based selection process/matrix, can form an appropriate basis for overlapping and narrowing independent solution sets;

$H3_1$: The transition from the aerospace traditional PD to LPD in a product lifecycle perspective and, by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework, can be achieved through the implementation of a holistic model.

It was pointed out, while summarizing the research opportunities, that the effects of major SBCE practical implementation enablers (e.g. configurability) on the development process performance are rarely studied, whether by experimenting alternative hypothesis or disproving null hypothesis. It is therefore proposed in this research to evaluate H1 null hypothesis for configurability depending on the availability of the setting:

H1$_0$: The lack of configurable virtual product has no impact on flexibility, time, costs and furthermore SBCE during a product development program.

Disproving null hypothesis is said in the research design literature to lead to positive conclusions about grounds for believing that there is a relationship between two phenomena, which then strengthens the alternative hypothesis (Trochim & Donnelly, 2000).

Next sections will discuss the appropriate research paradigm and approach to validate the hypotheses as well as to refute the selected null hypothesis.

3.2 Classification of the design research

According to Hubka and Eder (2012a), "Design science is to be understood as a system of logically related knowledge, which should contain and organise the complete knowledge about and for designing". Designing as emphasized is, for example, "the process of applying various techniques and scientific principles for the purpose of defining a device, a process, or a system in sufficient detail to permit its physical realisation" (Taylor, 1959) or "a purposeful activity directed towards the goal of fulfilling human needs, particularly those which can be met by the technology factors of our culture and, Decision-making in face of uncertainty" (Asimow, 1962). Design is referred to with many variations. It is primarily an action in terms of design activities and design process but also the actual output of a design process. As Design (action) spans several knowledge disciplines, including cognitive and behavioral neuroscience, psychology, sociology, complexity science, decision theory, calculus, computer science and cybernetics to name a few, it is sometimes debated that design research is not scientific, at least as compared to the sophisticated theories, research methodologies and procedures of some of the field sciences it involves (Eckert, Stacey, & Clarkson, 2003). Such debate has shown irrelevant because Design research is inherently multidisciplinary and may therefore be conducted according to the specific aspect/question the Design research is attempting to resolve. In all cases, design research is fairly differentiated from the related disciplines by firstly being "concerned with a complex creative and heterogeneous human activity" that produces design artefacts as a whole; and secondly, "concerned with finding practical ways to improve human performance in complex tasks" (Eckert et al., 2003). Indeed, design research is a scientific field of its own right which is related to Engineering Sciences. It has been a research-intensive field since the 60's with the purpose of understanding, modelling and building a theory of Design (Cross, 1984; Hubka & Eder, 2012a). Design research is dual-faceted. It is both involved with the interpretation of designing as a phenomenon (*understanding*) and the improvement of the process being studied (*support*) (Blessing & Chakrabarti, 2009; Eckert et al., 2003). To elaborate, developing understanding refers to studying the designer, the activity, the object, the context in which the activity takes place and the context of use of the resulting artefact in order to build and verify theories on designing as a phenomenon. Developing support, as it pertains to the larger part of this thesis, refers to creating knowledge, processes and tools to support the design activity in relation to the context in which it is performed. Hubka and Eder (2012a) propose a classification of design research that is shown in the form of a radar or a compass below. The axis and poles of the compass are meant to classify a research by the subject (object, technical system vs. process) and the output of the research (descriptive theory building statements vs. prescriptive statements to improve the process or the technical system). As an example, developing *understanding* as described by Blessing and Chakrabarti (2009) would correspond to the lower half of the compass while developing *support* would better fit with the upper part.

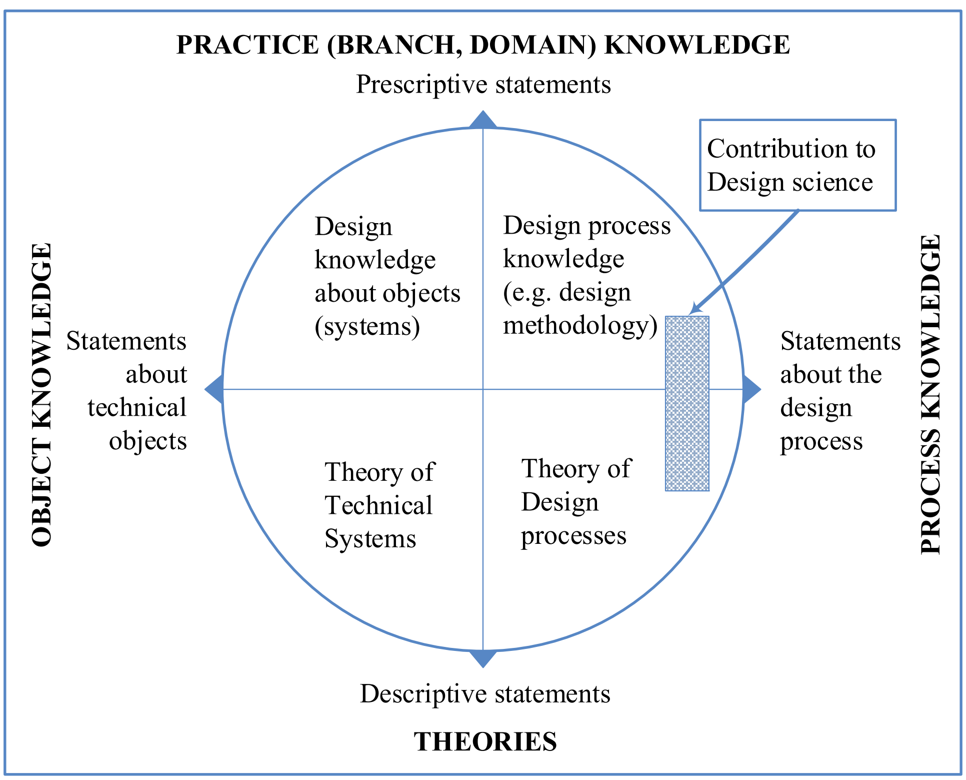


Figure 3.1: Classification of Design Science. Adapted from (Hubka & Eder, 2012a)

The contribution to Design science of the current research is reflected on the figure. As depicted on the radar, the contribution's footprint sits on the two quadrants on the right side because it is involved with developing understanding of SBCE (knowledge) as a Design process on one hand, and, on the other hand, improving this process while developing supporting tools and methodologies.

Chapter 2 (review of the literature) has contributed to understanding of SBCE (knowledge), the state of the art in the field and the research opportunities with regards to the current research. These opportunities have been formulated into questions that the research attempts to answer by validating the hypotheses. As observed during the design of the SBCE dual analysis framework, SBCE belongs to the lean philosophy and it consists in foundational theories and principles that are shared and accepted within the community and believed to be further theorized through reasoning, experience and research. This is to say, the SBCE philosophy, theories and principles, as discussed during the systematic review, are collectively accepted, not reconsidered but rather studied and implemented in a constructivist-pragmatist way in order to confirm the premises or formulate a more complete theory of set-based design. The current research will adopt the same stance. Likewise, the research questions correspond to inquiries into the interdisciplinary interactions within the design and product development process while discovering and understanding the enablers and catalysts of the practice of SBCE in a context-specific setting i.e. aerospace product development, multi-domain product structuring practices, configurable virtual product and harmonized prototyping practices. This suggests a research of a qualitative type which may potentially use elements of quantitative analysis to make sense of the data in order to derive qualitative conclusions. Such use of quantitative analysis has already proven effective for the systematic review of data extracted from the research publications databases, see chapter 2. It was observed during the systematic review that SBCE research is marked by this common pattern inquiries (due to the state of the research in the field), which then makes SBCE research, as it stands now, predominantly qualitative, inductive, and proceeding through natural inquiries. The current research does not constitute an exception in that sense.

The selection of the appropriate method(s) for the current research is influenced by two factors:

- The research objective, which is towards identifying key practical SBCE catalysts in order to cohesively study them and develop models and methodologies that can support the transition from traditional PD to LPD and SBCE. This denotes a requirement to develop conceptual frameworks following the exploration of the theoretical framework. The research is then viewed as conceptual from this perspective.

- The practical implications of the research and the direct involvement of the author into the lean Product Lifecycle Management (PLM) transformation of a manufacturer of complex aerospace systems. As a business consultant and architect in PLM, the author is actively engaged with its community in a vast program, spanning several years, with the purpose of transforming their processes and integrating their value streams into an end-to-end lifecycle process (inception to service) supported by lean practices and modern PLM technology. This calls for action research (practical/participatory) as the research typically involves the author in a community, developing understanding of phenomena and answering questions to proactively transform the community or to define how change can occur in the community (Creswell et al., 2007; Paillé & Mucchielli, 2016).

While the research, by its nature and objective, necessitates the research-based, model-based and pilot approach, the natural settings of the author's community transformation also prompts ethnomethodology to study the concepts, artefacts and methods people use in the community for understanding and producing the social order in which they live (Bucciarelli, 1994; Button, 2000). It is commonly agreed that engineering design is not a purely technical activity but also a social activity, involving the complexity of social organisation (Bucciarelli, 1994; Lloyd, 2000). This may necessitate ethnographic approaches in order to understand and better study many aspects of the design and development activities. Fieldwork and ethnomethodology are therefore increasingly advocated within the engineering design research community with evidences of the positive impacts on the research as well as the new insights into Design they can provide (Bucciarelli, 1994; Button, 2000; Lloyd, 2000; Lloyd & Deasley, 1998). For the current research, observations, experience, structured focus groups (transformational workshops campaign), two pilot simulations and a real life experimentation represent the main source of data for the study. Corporate artefacts such as manuals, process maps, operating procedures, work instructions, internal documents, databases, etc. also represent valuable sources for the data collection. Qualitative coding (Strauss & Corbin, 1990), displays (Miles & Huberman, 1994), content analysis and analytical memos (Maxwell, 2012; Miles & Huberman, 1994; Strauss & Corbin, 1990) are used as the main techniques for arranging and presenting the captured data with the purpose of facilitating insight, comparison, and the development of the theory and proposed methodology.

The figure below summarizes the current research paradigm (highlighted) in the context of the SBCE research analysis framework introduced in chapter 2.

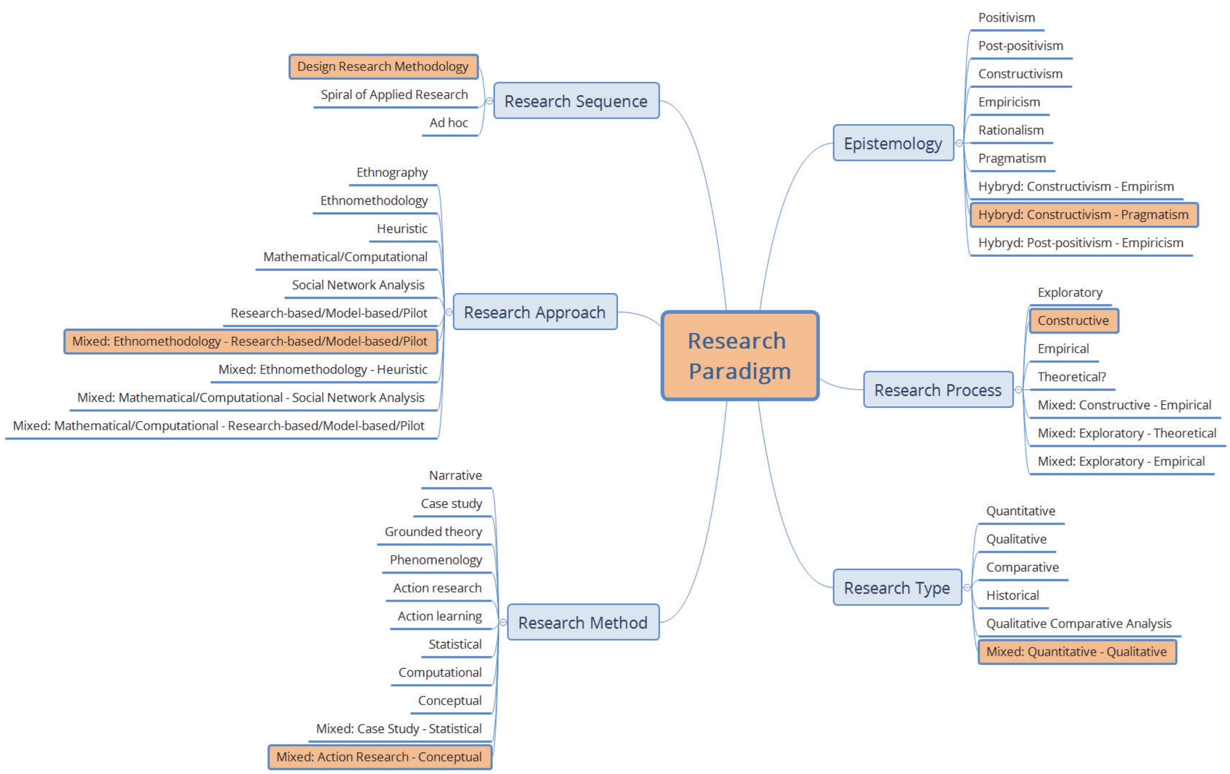


Figure 3.2: Research paradigm

The previous positions the research from an epistemological and overall paradigm standpoint. Next section elaborates on the overarching methodology that is used for planning and executing the design research project while ensuring that focus is placed on achieving substantial progress with regards to understanding and implementation of SBCE and LPD as Design practices.

3.3 Research methodology

The general research methodology selected to structure this research is the Design Research Methodology (DRM) developed by Blessing and Chakrabarti (2009). Figure 3.3 below displays the adopted DRM framework.

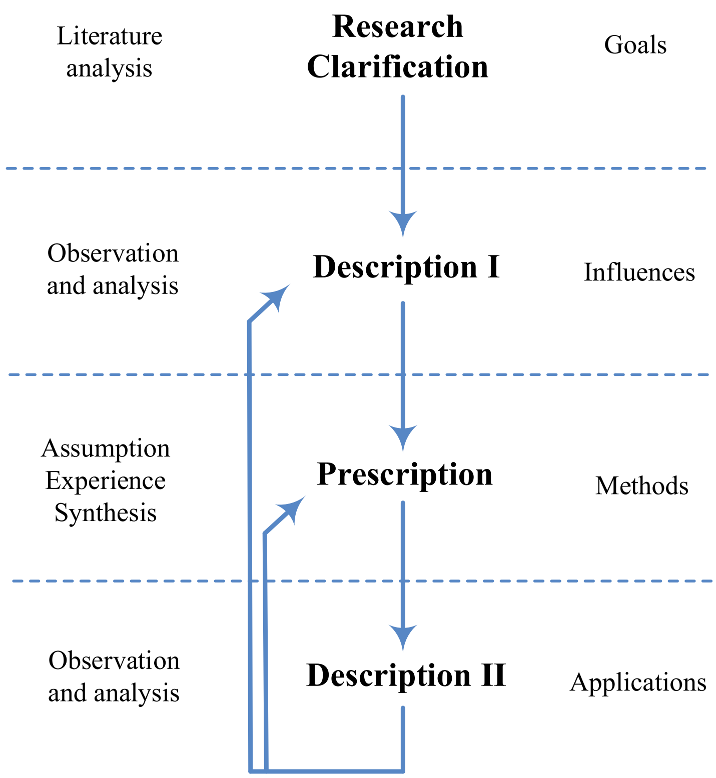


Figure 3.3: A Methodology for conducting design research. Adapted from (Blessing & Chakrabarti, 2009)

The main stages of the methodology are: Research Clarification/Criteria Definition; Descriptive Study I; Prescriptive Study and; Descriptive Study II. DRM can be performed in one straight sequence but it should preferably run through iterative loops with the purpose of progressively firming up each stage with the outcomes of the next ones. It is argued that the framework, and its standard procedure for achieving tangible deliverables, can effectively guide a design research project through understanding of design phenomena, the development of supporting tools and methodologies and ultimately, the evaluation of these tools/methodologies for the sake of both deepening knowledge about designing and improving the current practice (Blessing & Chakrabarti, 2009).

3.3.1 Research Clarification

Research Clarification stage involves defining the context and focus of the research as well as identifying the goal that the research is expected to fulfill. This is usually performed through literature reviews as well as real life experience, observations and objectives from industry. The comprehensive literature review of lean thinking and lean product development, an evidence-based systematic literature review of SBCE and the resulting synthesis and research opportunities/objectives form the main part of this stage. See chapter 2. The author being involved in cross-industrial communities of practice as well as directly working towards the transformation of the Product Lifecycle Management (PLM) process and supporting tools of a lean manufacturer of complex aerospace systems, his experience, observations and analytical memos have also fueled this stage. This research project is intended to contribute to both academic knowledge and current practice regarding SBCE and LPD. The success criterion is therefore that results should contribute to other academic research projects and should be applicable in industry.

3.3.2 Descriptive Study I

Descriptive Study I focuses on identifying the factors that influence the phenomenon or process under study. A detailed understanding of the problem is formulated in this stage through extended literature review and exploratory case studies and simulations. The problem definition and the context for which the validity of the research results should be considered are clarified. As-is situation and potential enhancements are also documented, serving as a reference for comparison and transition to a future improved state. The comprehensive study of Design prototyping and digital product information practices in industry forms the extended review from which key aspects to consider towards enabling set-based prototyping within state of the art PD information framework are highlighted. The main reference for the study is the combination of comprehensive literature reviews of the topics as well as data gathered from an industrial workshop campaign i.e. structured focus groups. Figure 3.4 below shows a dashboard from the industrial workshop campaign conducted as part of Descriptive study I.

Category	Key Reviewers Org. (Must attend the review)	Design Decisions	Schedule	Team review
3D Representations and Practices	2,3,5,8,9,10	11	Session 4 - April 14, 2014	Yes
BOM Contents, Disposition and Transition	2,3,4,5,6,7,9	18	Session 1 - April 2, 2014	Yes
CAD Practices	2,3,8,10	6	Session 9 - May 5, 2014	Yes
Configuration Control and Dispatching	2,3,4	6	Session 4 - April 16, 2014	Yes
Document Creation, Classification and Lifecycling	2,3,4,7,8,9	5	Session 9 - May 5, 2014	Yes
Enterprise Technical Instructions	5,9	10	Session 8 - April 30, 2014	Yes
Legacy Data Management	1,2,4,9	3	Session 9 - May 5, 2014	Yes
Part / BOM Change Practices	2,3,4,5,6,7,8,9	17	Session 7 - April 28, 2014	Yes
Part Creation, Classification and Lifecycling	2,3,4,5,7	8	Session 2 - April 9, 2014	Yes
Product / Part Data	2,3,4,5,6,7,8,9	10	Session 3 - April 9, 2014	Yes
Product Breakdown, Logical Decomposition and Configuration	1,2,4,5,7,9	11	Session 5 - April 16, 2014	Yes
Product Development Practices	1,2,3,4,5,7,8,9	13	Session 6 - April 23, 2014	Yes
Mix (Remaining)	**As required**	(5)	Session 10 - May 7, 2014	Yes
Mix (New DDs + Remaining)	**As required**	(12+3)	Session 11 - May 12, 2014	Yes
Key reviewer organisation	**Total**	**118**	**11 Sessions / 33 Hours of Team Reviews / 40 Days**	**Done**
1-Advance Engineering	**Critical**	**22**		
2-Design Engineering	**High**	**48**		
3-Product Definition and Integration	**Medium**	**38**		
4-Configuration Management/Change Control	**Low**	**10**		
5-Process Planning/Manufacturing				
6-Operations/Quality				
7-Development Engineering/Experimental				
8-Analytical/Simulations				
9-Service/Aftermarket/Publications				
10-CAD Specialist				

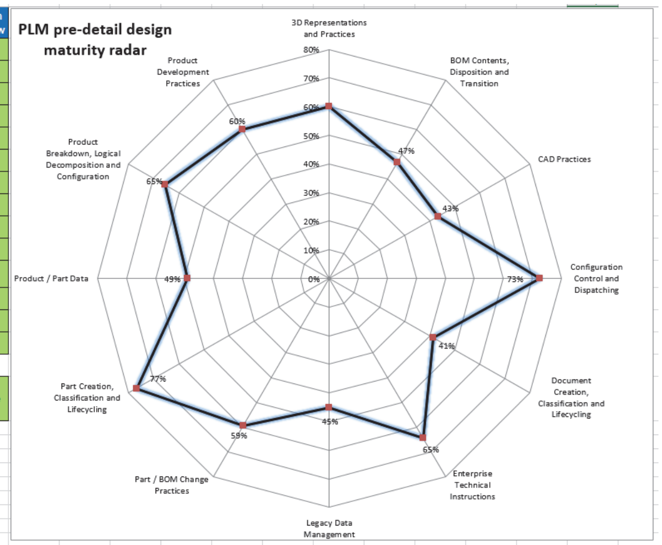


Figure 3.4: Descriptive study I structured focus group dashboard

This industrial workshop campaign explored the different facets of the company's development process as well as the resulting synchronisation with experimental/operational value streams from a prospective lean PLM transformation. Structured focus group procedures share similarities with convergent interviewing by using a structured process and unstructured content so that information is gained from participants rather than being determined by the questions asked (Jepsen & Rodwell, 2008; Stewart & Shamdasani, 2014). The procedure was followed during the campaign by asking questions upfront in terms of design decisions, allowing participants to think, analyse company artefacts, discuss and orient the debate during team reviews, then answer based on their shared understanding and vision of to-be state.

The comprehensive literature review and structured focus group campaign are complemented with a research-based study simulating the design of new mountings for the retrofit of an aircraft engine. This is done in order to fully satisfy Descriptive study I stage by simulating and further validating the identified potential influences towards practical SBCE implementations. The dataset and reference framework described in the study are from the Product Development and Systems Integration (PDSI) student project held each year at Polytechnique Montreal (Fortin, Huet, Sanschagrin, & Gagné, 2006). This reference is selected because the PDSI project has proven, over the past dozen years, to be a very unique and worldwide acknowledged replicator of aerospace product development practices. Also, there is an advanced and extensive use of PLM, DMU and virtual prototyping capabilities within this project.

Finally, a real life experience is reported as part of this Descriptive study I to further validate identified influences towards practical SBCE implementations. This real life experience is also used to report on the influence of the absence of configurability capabilities on the product development and product evolution process, thereby disproving null hypothesis **$H1_0$**.

3.3.3 Prescriptive Study

In this third stage, theories, concepts and models describing the nature of the problem and the potential solutions and tools are synthesised into a prescription to support the improvement of the current state. The main prescription in this thesis consists in the proposal of a multi-domain product structuring model that can support implementation of SBCE in the context of practical influences identified in Descriptive study I. As expected, Descriptive study I and Prescriptive study were performed following an iterative process orienting and refining the research onto the key aspects to study, improve or construct.

It is argued that the E-FM tree model of the design process (Johannesson & Claesson, 2005) can be transposed into a theory of domains representational formalism for lifecycle management, then combined with generic product structuring language (Erens, 1996; Wortmann & Erens, 1995) and developed into the physical instantiation domain (Huet et al., 2011; Männistö et al., 2001; Toche et al., 2012) in order to form a new product structuring model that can enable SBCE in a lifecycle and industrial PD framework perspective (**$H1_1$**).

It is also claimed that the resulting product structuring model, combined with virtual prototyping practices and set-based selection matrices, can form an appropriate basis for overlapping and narrowing independent solution sets (**$H2_1$**). The approach leverages advances in digital prototyping practices i.e DMU supported, and virtual factory simulations, to advocate the potential for each discipline to develop their own solution sets virtually (Nemawashi), then overlap with others within the virtual space. This can support the elimination of unfeasible design alternatives based upon centralized past project data, solution set clashes and incompatibilities identified while simulating design solutions within the virtual space. As each design alternative is materialised by a separate configuration from the product structuring model, it is possible for all stakeholders to communicate on the basis of the multitude of possible solutions at a given time and, therefore, document them accordingly. When required, physical instantiation of a design alternative can be performed, representing a physical prototype that is built, tested and for which all the gathered data is associated with the product-model-instantiated and configuration-tracked structure. The method is extended to include flying instances of the product. The data, as maintained against each design configuration and the potential prototype instances, is used to inform the current and future set-based selection processes/matrices. The approach, as described, is valuable in fostering a product lifecycle oriented and enterprise-level structured Knowledge-Based environment with the purpose of continually implementing and improving a company practice of SBCE and LPD. The components of this approach and the product structuring model form the basis for extrapolation (**H3$_1$**) to the Learning Value Streams (LVS) model displayed below.

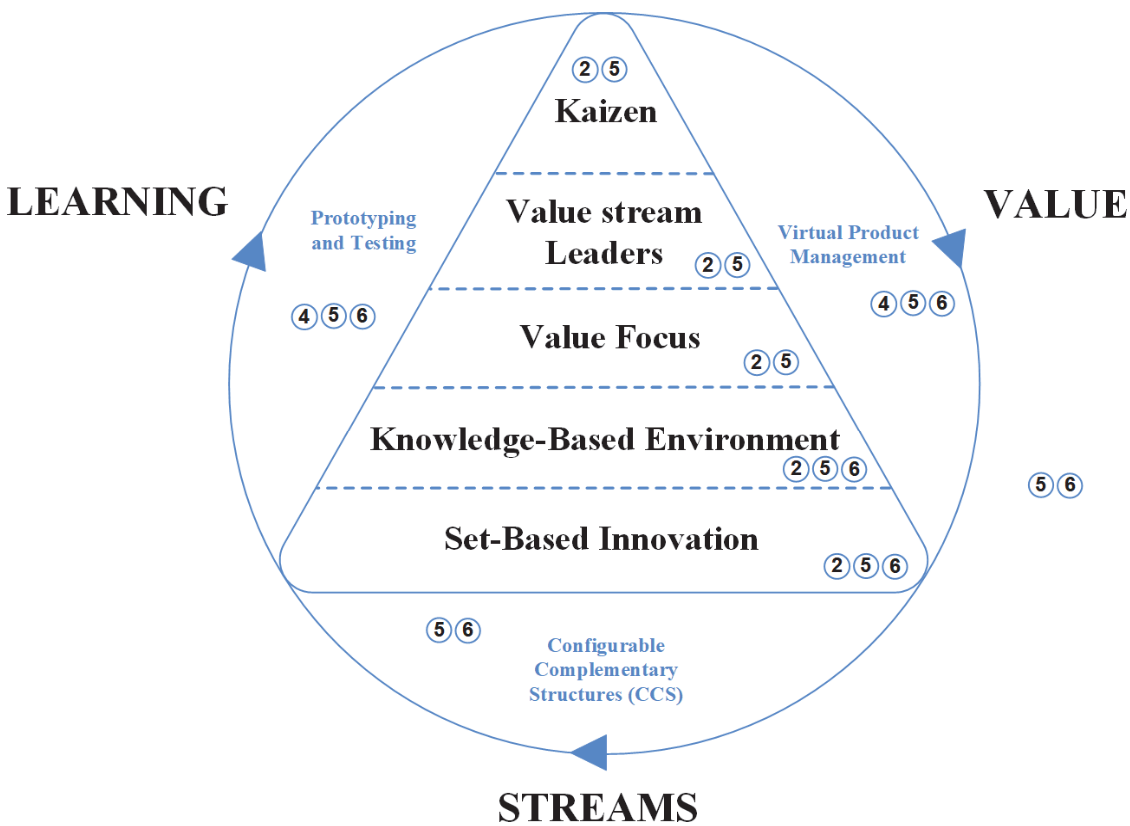


Figure 3.5: Correlation between the thesis chapters and the components of the LVS model

The LVS model, developed through DRM iterations, encompasses practical SBCE enablers and catalysts in a coherent whole that can holistically support the transition from the aerospace traditional PD to LPD in a product lifecycle perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework.

3.3.4 Descriptive Study II

The last stage, Descriptive Study II, consists in evaluating the prescribed approach and tools by validating them against the criteria through additional case studies and preferably in a realistic design context. It is difficult for many design research projects to successfully cover this stage because the resources, settings and readiness of the tools or methodologies are rarely available to benchmark the proposal within an industrial context and without disrupting established practices too much. In this thesis, as a business consultant and architect into the transformation of the PLM processes and supporting tools of a lean manufacturer of complex aerospace systems, the author has unique opportunities in terms of business process modelling as well as software rapid prototyping and testing. It is then possible for the author to prototype and simulate advanced processes and methodologies leveraging customized instances of the existing operational PLM virtual product management platform. The second pilot simulation presented in chapter 6 forms the main part of descriptive study II. The study consists in a pilot simulation of the proposed product structuring model through the exploration of three design alternatives of an aircraft pylon in the context of a realistic enterprise PLM platform. Figure 3.6 illustrates the proposed pilot study.

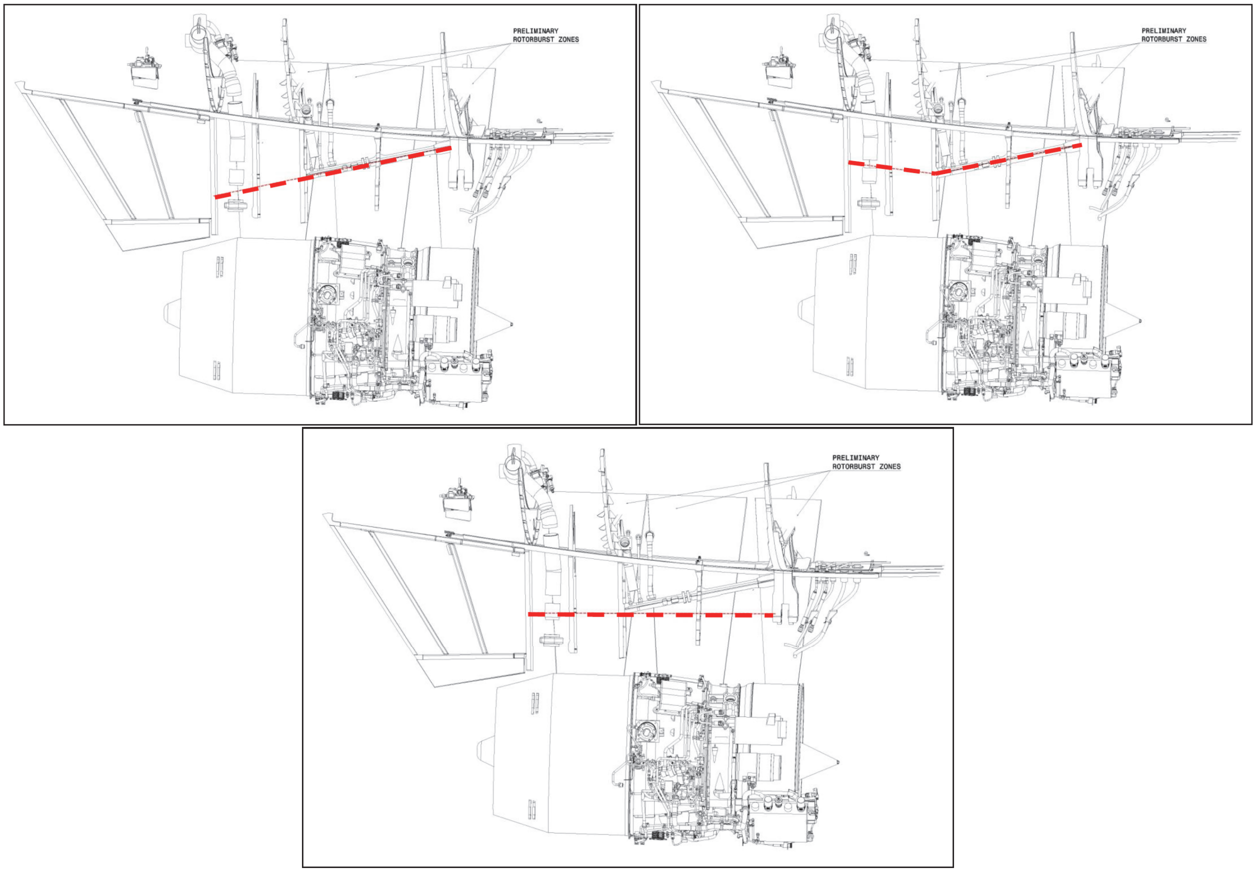


Figure 3.6: Engine Firewall design options (product configurations)

A team composed of the author, one system engineer, one development and test engineer, one product definition integrator, three designers (interns) and one CAD/DMU specialist participate in the simulation. The figure below illustrates the context of the validation. The exhibit shows a configurable BOM, synchronized with the related configurable DMU (lightweight view for non CAD authoring) as they are being loaded by the author in one advanced version of the enterprise PLM platform.

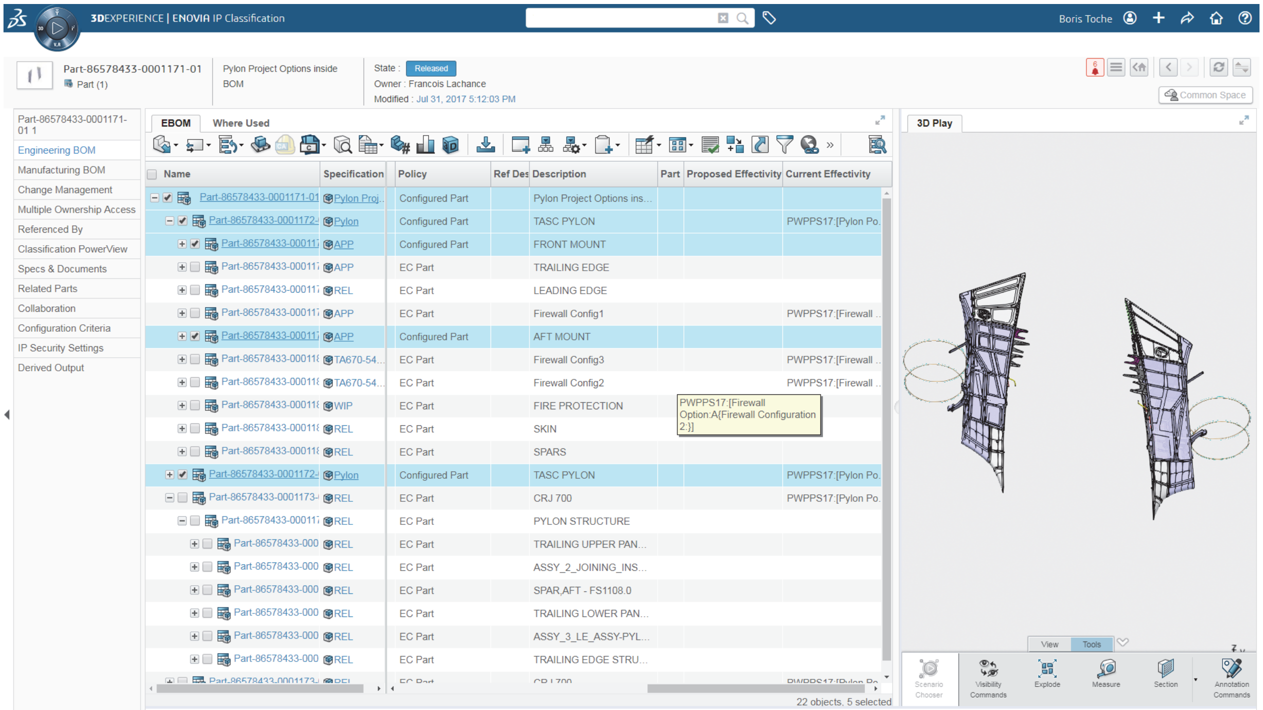


Figure 3.7: Dataset in the simulation environment (fuselage, engines and nacelles not shown) - Courtesy of Dassault Systemes, **3D**EXPERIENCE 2017x

To recapitulate, the table below shows the thesis organisation in relation to DRM as applied.

Table 3.1: Thesis chapters in relation to DRM sequence

Thesis Chapter	Chapter Title	**DRM**	Chapter Description
1	Introduction		Research background, motivation, main objective, thesis structure.
2	Literature review	**Research clarification**	Comprehensive literature review of lean thinking and lean product and process development.
			Evidence-based systematic literature review of SBCE (1987-2017). Synthesis Research opportunities.
3	Methodology		Research objectives, questions, hypotheses and criteria. Research paradigm and methodology. Research validation.

Table 3.1 (Cont.): Thesis chapters in relation to DRM sequence

Thesis Chapter	Chapter Title	**DRM**	Chapter Description
4	Design prototyping and the digital product information	**Descriptive study I**	Comprehensive study of design prototyping and digital product information theory and practice. Synthesis of gaps and proposal of a methodology to support collaboration during prototyping and testing in a PLM perspective. Research-based case study (Pilot simulation I). Experiences in industry
5	Construction of the Learning Value Streams (LVS) model	**Prescriptive study**	Construction of the Configurable Complementary Structure (CCS) model towards SBCE. Extrapolation to the Learning Value Streams (LVS) model.
6	Product structuring pilot simulation	**Descriptive study II**	Simulation of the proposed product structuring methodology by leveraging a commercially available PLM platform (Pilot simulation II).
7	Conclusions and recommendations		Summary of the findings, contributions, applications and recommendations for future research.

An iteration path was followed while applying the design research methodology as depicted in Figure 3.3. The two pilot simulations were performed using two separate commercially available and major aerospace industry PLM platforms. This was done on purpose in order to independently assess the proposed methodologies, infer PLM platform-neutral conclusions and allow for triangulation in the research.

The thesis is structured towards the definition of the role, the construction and evaluation of the components of the proposed LVS model and the integration of the components into a whole. The thesis is simultaneously aligned with the DRM sequence presented in this section.

The research may similarly be structured in relation to other existing design research frameworks like the spiral of applied research framework by Eckert et al. (2003). However, this framework, for example, is suitable for large research projects that involve a number of researchers working on several themes over an extended period of time, which is not the case here, and therefore the reason why the DRM framework was preferred.

3.4 Conclusion

Based on the research objectives, inquiries, hypotheses and the involvement of the author in a community seeking for change towards lean product lifecycle management, the research is designed as a mixed quantitative-qualitative type, proceeding through a mixed conceptual-participatory action research and by choosing a mixed ethnomethodology-research-based/model-based/pilot simulation approach. As far as qualitative research is concerned, the use of reliability, validity and furthermore triangulation (to test the first two) are common in quantitative research but this is not straightforward in the qualitative research paradigm as the concepts may bear different meanings (Golafshani, 2003; Maxwell, 2012). Golafshani explains that reliability and validity can be conceptualized as trustworthiness, rigor and quality in qualitative research paradigm, focusing on the output of the research, the methods and the researcher as the instrument of the research. In other words, it is through precision, consistency, credibility, confirmability, applicability and transferability that a qualitative research can achieve reliability and validity by eliminating bias and increasing the researcher's trustworthiness in its proposals (Golafshani, 2003). Then triangulation is perceived to be a validity procedure that relies on multiple methods of data collection and data analysis, leading to a more valid, reliable convergence to the themes, categories and interpretations formed in a study (Creswell & Miller, 2000). The current research is designed to meet the qualitative research criteria as just described. One example worth citing in this summary is the triangulation that results from performing pilot simulations in two separate commercially available and major aerospace industry PLM platforms in order to independently assess the proposed methodologies and infer PLM platform-neutral conclusions. The approach followed in chapter 2 for the literature review and, especially the design and conducting of an evidence-based systematic review of SBCE, also exemplifies the commitment. The remaining part of this thesis work fulfills the criteria in the same vein.

Besides the epistemological stance and research paradigm, an overarching Design Research Methodology (DRM) is selected to conduct the design research. From this standpoint, the use of success criteria for action research in design, as initially advocated by Blessing and Chakrabarti (2009) has been criticized because success criteria are believed to focus the study on (sometimes invalid, unreliable) metrics, disregarding unanticipated influences by simply paying too much attention to the so-thought measurable premises (Eckert, Clarkson, & Stacey, 2004; Reich, 1995).

Success criteria are believed to be “of limited utility in evaluating the success of introducing new tools, methods and procedures into design processes in industry” (Eckert et al., 2004). According to the authors, the most useful criteria for success is the advancement of knowledge i.e. understanding design, and the perception of value in new procedures and methods by practitioners in industry. These criteria are retained for the current research. Chapter 2, for example, has previously been evaluated against the first criterion, which evaluation demonstrated success through two main contributions: (1) the proposal of a new SBCE dual analysis framework combined with an evidence-based systematic review methodology and; (2) the advancement of theoretical and practical understanding of LPD and SBCE from the larger to the most significant aspects. The remaining part of this thesis work provides additional contribution to understanding of LPD and SBCE and furthermore, entails valuable proposal for the practice of LPD and SBCE in industry through the CCS model and the construction of the LVS model.

CHAPTER 4 DESIGN PROTOTYPING AND THE DIGITAL PRODUCT INFORMATION

The previous chapters discussed the reasons behind the existence and, especially, the multiplicity of prototypes in a set-based approach to the design of complex products. The power of physical and virtual prototypes in mitigating uncertainty, risk and consistently driving innovation and learning through design space exploration is exposed in this chapter. The literature and body of knowledge about design prototyping of systems and services is first examined. Unique qualities and applications of both physical and virtual prototypes are presented by stressing the multiple dimensions from which prototypes can be perceived and planned accordingly. The shift from physical prototyping practices towards full virtual prototyping is then discussed and the required optimum level of combination between the two is emphasized for an efficient overall prototyping practice in LPD and SBCE. Digital product information in the context of PD and PLM is presented in the second part by detailing foundational elements of *product information*, *product data*, virtual prototyping, Product Structure Management (PSM) and the complementary information product structuring model. Identified as a missing component towards streamlining PLM prototyping processes, a novel *as-tested* structure is introduced and elaborated in this chapter to allow collaboration during prototyping and testing in a PLM perspective. The proposed methodology is validated through a case study simulation as well as industrial experience involving components of the proposal. Null hypothesis $\mathbf{H1_0}$ is finally disproved in this chapter based on a unique experience from the same industrial context. Design prototyping and digital product information developed in this chapter explore the second influential aspects (first is SBCE and LPPD enablers examined in chapter 2) towards the prescription in chapter 5.

4.1 Prototyping activities in SBCE

Wheelwright and Clark (1992) represented the SBCE convergence process with the *development funnel*, where a respectable amount of alternatives is put into several Design-Build-Test cycles.

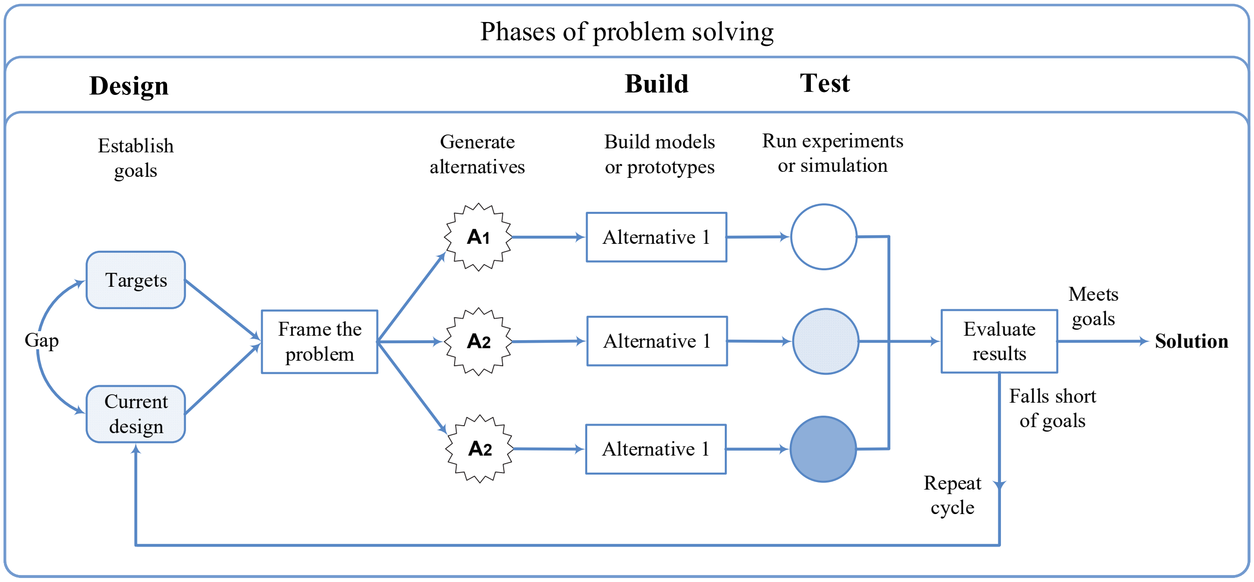


Figure 4.1: Design-Build-Test cycle. Adapted from (Wheelwright & Clark, 1992)

As time progresses, quantitative and qualitative data are gathered through simulation and test. Inferior alternatives are screened and only the most promising move forward into the funnel, until the best is produced and delivered to the customer (Wheelwright & Clark, 1992). Denso, a first-tier supplier of Toyota, has brought such a process to finely tuned art and makes set-based design a gage of perpetual business superiority as witnessed by Ward et al. (1995). Only one year after establishing general design targets, Denso's engineers have already created full or partial prototypes evaluating their ideas as much as they can. By combining ideas and leveraging trade-off charts, graphs and past test data, Denso's engineers experiment extensively. They funnel their effort and after four years of development they are handling about three different designs with five prototypes each. At the end of the fifth year, they may submit two of them to Toyota for series production while being strongly confident in one superior design.

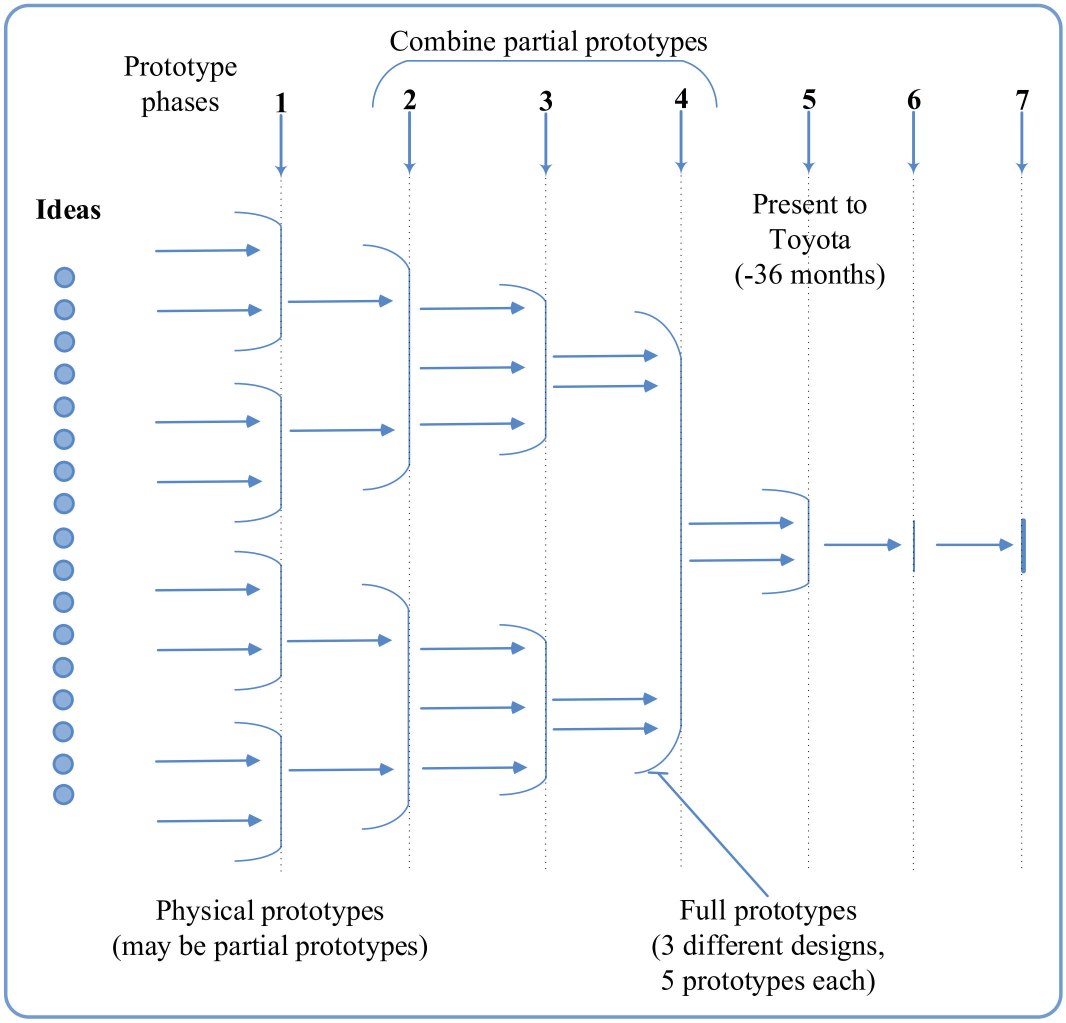


Figure 4.2: Denso's R&D Process. Adapted from (Ward et al., 1995)

At the same time, Denso furthers all its most promising alternatives into product families producible on the same lines. The approach is called *standardized variety* (Ward et al., 1995) and it gives Denso both the agility and capability to face current and future market trends. By multiplying prototypes, set-based design practitioners extensively explore opportunities and consistently generate knowledge to converge to superior designs or at least, optimal ones. They use extensive exploration of the design space to assess and enable more variability while creating real options that increase the company's competitive advantage on the long run. Such correlation has computationally been evidenced by Schafer and Sorensen (2010). These authors used the extended net present value (ENPV) and option valuation to assess the total value of the development process in point-based iteration vs. parallel options exploration. They conclude on superior performances in terms of flexibility and long-term value provided by exploring multiple options in set-based design approaches to prototyping. Indeed, SBCE culture of alternative designs exploration is a common practice in engineering design (Baxter, 1995; Cross, 1989; Hubka & Eder, 1987; Pahl & Beitz, 2013; Pugh, 1991; Ullman, 2009; Ulrich & Eppinger, 2012; Wheelwright & Clark, 1992) and it does not necessarily distinguishes SBCE from the other PD paradigms. In practice, it is the time and effort spent handling, exploring and documenting multiple alternatives long into the development process that makes SBCE different. SBCE design space awareness and thorough exploration extends the classical vision by enabling a broad discovery of the design space to avoid narrowing too quickly on discrete areas of the space and thereby, losing the potential for innovation and discovery. Although the importance of prototyping and testing is well understood in SBCE literature, there is a strong focus on trade-off curves as discussed in chapter 2, as they allow synthesis and visualization of large amount of information gained from prototypes, simulations and testing (Araci et al., 2016; Maksimovic et al., 2012). Potential other facets of design prototyping and furthermore learning by experimentation, as they influence SBCE and LPD are rarely addressed. There is a lack of understanding of prototype information tracking and reuse, especially in more frequent cases where complex phenomena is not synthesized into trade-off curves and where information (configurations, test results, performance data, best practices, etc.) from past experimental references is rather used as-is to accelerate the synthesis and assessment of design solutions. These experimental references form the basis of the comparative data (reusable knowledge) advocated in LPPD along with trade-off curves (Ward & Sobek, 2014) p.140. Better understanding and supporting learning by experimentation practices as well as prototype information tracking and reuse in industry is therefore relevant for both current practices and towards LPPD i.e. focus on enabling an environment that facilitates reusable knowledge for current and future development projects. To help companies better strategize their set-based exploration efforts, including the construction of trade-off curves, Ward and Sobek (2014) propose to divide their development projects into four categories as shown in Table 4.1. This approach is combined with probabilistic calculations to determine the optimal number of alternatives/prototypes to pursue given the probability of failure of a system or subsystem design (product of the probabilities for the individual concepts) as well as the expected cost of failure (cost to the whole system). The calculation is basically about reducing the risk of a development project failure by indicating areas that require broader evaluations (cheap, early in the PDP), which usually yields higher probability of success compared to the probability of failure that results from unknowingly pushing a potentially weak option far in the PDP. This is confirmed by (Camburn, Arlitt, Perez, Anderson, & Kun, 2017; Camburn et al., 2015a) through empirical research. By aggressively eliminating weak options early in the PDP and thereby confidently concentrating on robust areas that can guarantee flexibility, discovery and innovation, set-based approaches to design make prototypes planning/execution a key factor of success in development programs.

Table 4.1: Development projects categories: Guidelines for prototyping and exploration. Adapted from (Ward & Sobek, 2014)

	Project categories			
	Tailoring	**Strategic breakthrough**	**Limited innovation & reintegration**	**Research**
Focus	Targeted market breakthroughs	Vigorous product/process innovation	Speed; leveraging suppliers' prior to work	Good trade-off curves
Product profitability	Required	Required	Required	Not a criterion
Product family	Within existing	Create new	Within existing	Crosses family boundaries
Breadth of set	Very small	Very broad	Moderately broad	Driven by data needs
Trade-off and limit curves	Use existing	Create new or shift existing	Use existing	Create new or shift existing
Component innovation timing	Precedes development with some tailoring	Simultaneous	Precedes development	Follows development
Manufacturing approach	Use existing technology	Process innovations expected	Use existing technology	Varies by project

4.2 Prototypes in engineering design

The role of prototypes in product development and testing is discussed in this section from a broader perspective by including the unique qualities and applications of both physical and virtual prototypes. The optimum level of integration of these physical and virtual prototypes is explored, and key aspects concerning the implementation of prototypes within testing activities is presented.

4.2.1 Traditional prototyping

Prototyping and testing work is usually done during product development for three main reasons: evaluate and validate design choices, mitigate uncertainty through real life assessment and learn by experimentation (Otto & Wood, 2001; Thomke, 2008; Ulrich & Eppinger, 2012). In the aerospace industry, evaluating and validating choices generally aims at demonstrating performance and compliance with design objectives and regulatory authority. Mitigating uncertainty consists in bringing several bodies of knowledge into interaction so each one's influence is disclosed and taken into account as soon as possible. Learning by experimentation, on the short term, supports design convergence. On the long term, it spearheads the core organisational learning system at the root of set-based design methodologies as developed in chapter 2 and beyond.

Physical prototypes are generally built to examine design problems, including the evaluation and refinement of solutions, as well as measuring one or more of its core qualities of role, implementation, and look and feel (Houde & Hill, 1997). These qualities can be defined as follows:

- Role: The function and how it corresponds to the user's needs;
- Implementation: The constituent parts and the logic through which the product function is performed;
- Look and feel: The sensory experience of the user.

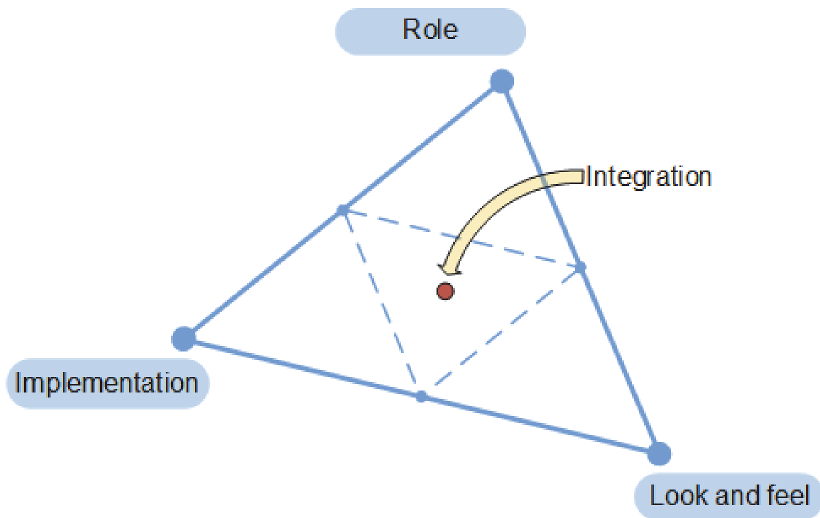


Figure 4.3: Three core qualities of a prototype. Adapted from (Houde & Hill, 1997)

Prototypes are also used during the PDP for four other main objectives: learning, communication, systems integration and milestones (Lazzari & Raimondo, 2001; Otto & Wood, 2001; Thomke, 2008; Ulrich & Eppinger, 2012). It is useful therefore to consider the prototype as an approximation of the product along one or more dimensions of interest (Blomkvist & Holmlid, 2012; Camburn et al., 2013; Dunlap et al., 2014; Hammon et al., 2014; Hannah, Michaelraj, & Summers, 2008). For example, a prototype can be classified according to the degree to which it approaches reality. This level of fidelity can determine the prototype's ability to detect unanticipated phenomena, which can be difficult with non-physical prototypes e.g. digital mock-ups (DMU), computational models, etc. (Gerber, 2009; Häggman, Honda, & Yang, 2013).

Ulrich and Eppinger (2012) note that some experimental prototypes are built and tested early in the design process, prior to the definition of the detailed part geometry, see Fig.2.3. These prototypes are thus based on lower maturity documentation created following the concept generation. Furthermore, they are usually built without using mass production infrastructure or tooling (Clark & Fujimoto, 1991). These prototypes are named *looks-like* and *works-like* models and serve the purpose of design concepts instantiation and evaluation. Prototypes at the testing and refinement phases are more mature approximations of the product and they effectively disclose a part of its actual behaviour and signal necessary changes, while considering the level of approximation.

The amount an organisation can learn from a physical prototype directly depends on its level of approximation. Table 4.2 presents three categories of prototype developed during the PDP, namely alpha, beta and preproduction. These categories are defined by the prototype's main objectives, its similarities with the production product, and its relevant deviations.

Table 4.2: Properties of typical physical prototypes categories. Adapted from (Ulrich & Eppinger, 2012)

	Main objectives	**Similarities**	**Deviations**
Alpha prototypes	Assess whether the product works as intended	Geometry, material	Production processes, suppliers
Beta prototypes	Assess reliability and identify remaining bugs in the product; Test in the intended use environment (by customers).	Geometry, material, production processes, suppliers	Assembly facilities and tooling
Preproduction prototypes	Verify production process capability First supplies to preferred customers	Geometry, material, production and assembly processes, suppliers	Full capacity production facilities

The objectives listed in the table deal primarily with assessing the concept performance and validating the supply and manufacturing processes. These include testing activities preceding the serial production. It should be noted that prototyping and testing activities are also carried out in the aerospace industry for certification issues, mature technologies introduction as well as for investigation of failures in the field. Prototyping and testing is therefore performed for the main part during the PDP but is not excluded from happening well earlier or well later during the product lifecycle. Figure 4.4 exemplifies aerospace industry practices by graphically showing the numerous physical prototypes that can be built and tested during the development of a complex aerospace system.

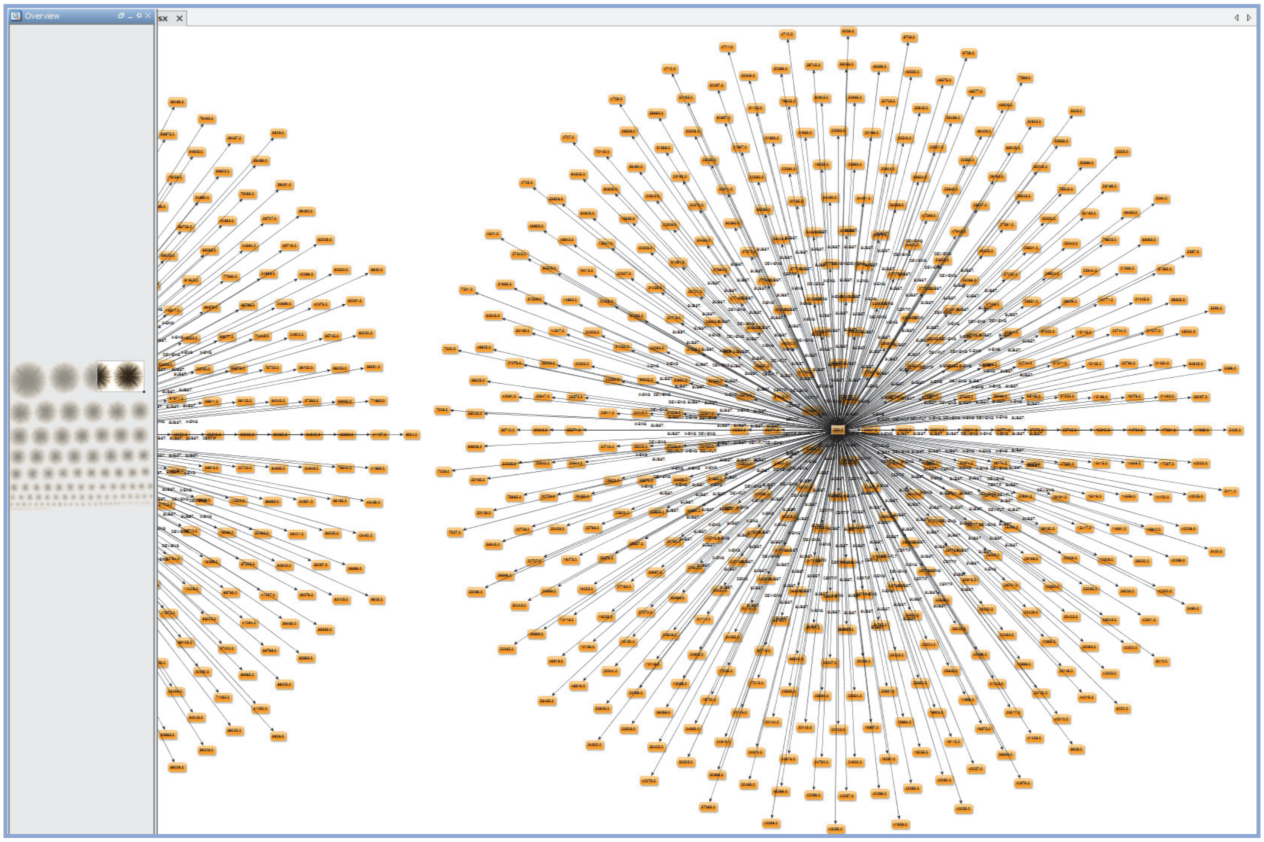


Figure 4.4: Experimental builds during the development of a complex aerospace system

The graph allows to visualize data as extracted from a legacy development and test information system and plotted using a graph editor. Each circular cloud on the left side of the exhibit represents the cluster of experimental builds for one development program or technology demonstration. It is possible to see that the number of physical prototypes that are built and tested varies according to the nature of the development program (NPI, derivation, TRL, etc.) and also, the extent to which the new product reuses existing proven technology, modules and components.

Besides the progressive level of fidelity selected while prototyping, it is not always easy to find an optimal approach to prototyping during a development project, especially when considering the variety of strategies and techniques that may exist to improve the outcome of the activity (Christie et al., 2012). Systematic methods for planning and executing design prototyping activities exist in the literature with the aim of improving the overall development cost and performance. For example, Camburn et al. propose a phased approach to systems prototyping which consists of the partitioning, search and implementation phases (Camburn et al., 2017;

Camburn et al., 2015a; Camburn, Jensen, Crawford, Otto, & Wood, 2015b). Partitioning defines the aspect from which the complex system is prototyped and tested i.e. by function, subsystem or domain e.g. usability, manufacturability, sustainability, etc. Search is performed either through an iterative testing of overlapping design concepts or the parallel testing of multiple concepts at a single point in time. These are equivalent to exploration strategies found in point-based vs. set-based design (Ward et al., 1995). Implementation is the actual prototype execution. Key prototyping techniques are synthesized from the literature (heuristics) to define three "conceptually distinct cost reduction techniques" i.e. scaling, isolation and abstraction. Mathematical equations are also proposed to assess the expected performance of iteration versus parallel testing on one side and, on the other side, assess the reduced prototyping cost that results from considering a scaling factor, an isolation factor, an abstraction factor or an eventual combination of these. The effectiveness of multiplying prototypes early in the design effort to later iterate on higher fidelity models is demonstrated in controlled studies using the proposed metrics (Camburn et al., 2015a) as well as a graphical representation of the design topological space exploration (Camburn et al., 2017). As reviewed in section 2.1 and 4.1, multiplying prototypes by favouring low fidelity, virtual prototyping, requirement relaxation and rapid prototyping is similarly believed in the lean paradigm to reduce development time and cost and to increase flexibility, development performance and a company competitive advantage on the long run (Hoppmann et al., 2011; Ward & Sobek, 2014). It is therefore vital for a company to carefully study the various strategies, dimensions and techniques while planning for prototypes during their development projects, especially when considering the cost of building prototypes (virtual or physical).

4.2.2 Full virtual prototyping and limitations

The virtual prototype, facilitated through the development of a complex Digital Mock-Up (DMU), should be perceived here as an integration of data from various sources to define the total product and its environments. It provides the means of visualizing any aspect of the product design, behaviour, its fabrication and assembly, and the environment it will be used in (Coyle & Paul, 1997; Gausemeier, Berssenbrügge, Grafe, Kahl, & Wassmann, 2011; Ottosson, 2002; Radkowski, 2011; Stark, Hayka, Figge, & Woll, 2011; Wang, 2002). While Computer Aided

Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM) have considerably improved part design and manufacture, via, for example, 3D models and numerically controlled production processes (Hirz, Dietrich, Gfrerer, & Lang, 2013; McMahon & Browne, 1993), they are limited in terms of enabling full systems-level engineering. The DMU, by leveraging CAD, is the key enabler for the development of virtual prototyping and virtual production control, and it is paving the way for systems-level design, simulation and test; Fig. 4.5 illustrates this envisioned shift. In this context, the DMU is used to assess the form and fit of assemblies of 3D solid models constituting the product, functional virtual prototyping aims to assess the operating function of the assembled product, and the virtual factory simulation is used to investigate the manufacturing and assembly of the product (Canuto da Silva & Kaminski, 2016; Lazzari & Raimondo, 2001; Mas et al., 2014; Menendez, Mas, Servan, & Rios, 2012; Ryan, 1999). Digital twin (Glaessgen, & Stargel, 2012; Tao et al., 2017), Virtual Reality (VR), Augmented Reality (AR) and Internet of Things (IoT) can be regarded as building blocks towards cyber-physical systems exploration, simulation and rendering.

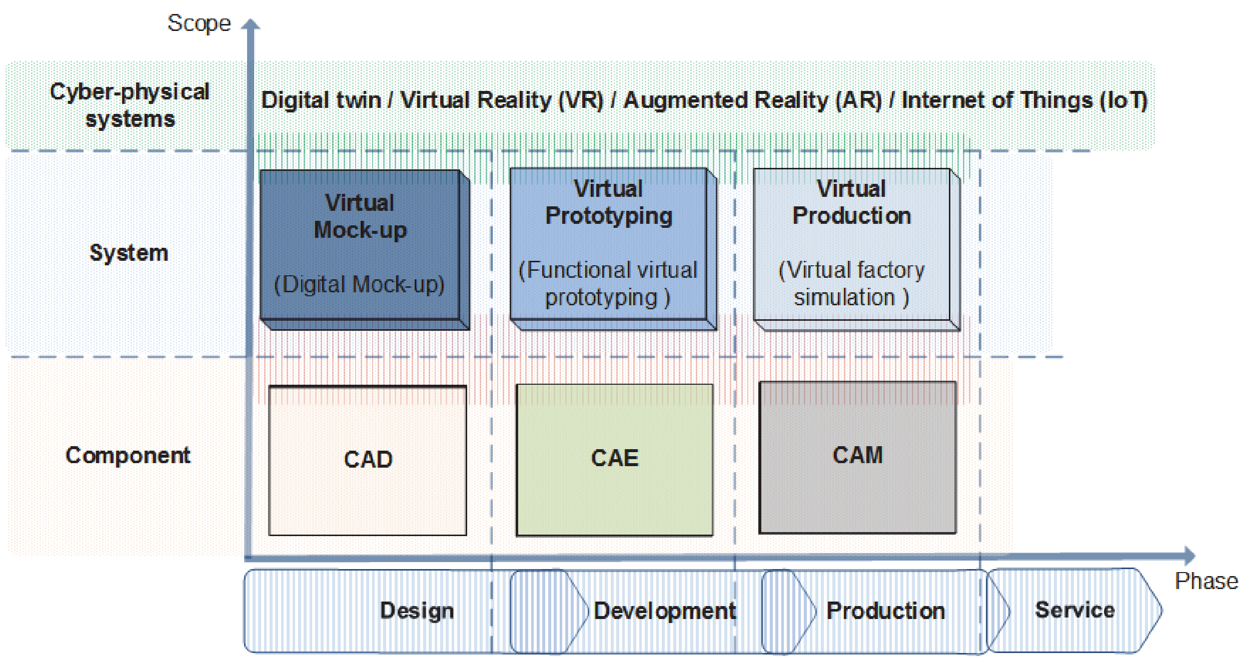


Figure 4.5: From component-focused CAD/CAE/CAM to system-focused virtual prototyping. Extended from (Ryan, 1999)

It can be argued that the systems-focused virtual prototyping provides the means to eliminate the expensive physical prototypes that currently must be built to verify the product functionality and behaviour. However, some crucial limitations, chiefly in functional virtual prototyping, are still present today. These are:

- Lack of technology and resources to accurately represent component behaviour and cross functional relationships under variable situations;
- Indispensable role of hardware prototypes in manufacturing organisation usages;
- Roadblocks to acceptance of process change, training and adoption.

4.2.3 Integration of physical and virtual prototypes

Since the former limitations remain true, the aim of enhancing the use of virtual environments during product development should be toward a synergistic use of both physical and digital representations, rather than the elimination of the first (Liu, Campbell, & Pei, 2013). In fact, physical testing is done with more confidence and can sometimes be executed more quickly and at a lower cost while providing tangible outcomes and rapid feedback promoting learning (Camburn et al., 2015a; Carleton & Cockayne, 2009). Van Der Auweraer et al. (2005) strengthen the view of mixing physical tests and simulations by indicating that physical test methods should be used to validate and calibrate simulation models and thereby extend the applicability of the latter. Figure 4.6 shows how the combination of physical tests and simulations delivers innovation. The vertical axis represents the required capability for certain engineering tasks, such as system verification, and the horizontal axis represents the overall effort needed to accomplish the tasks.

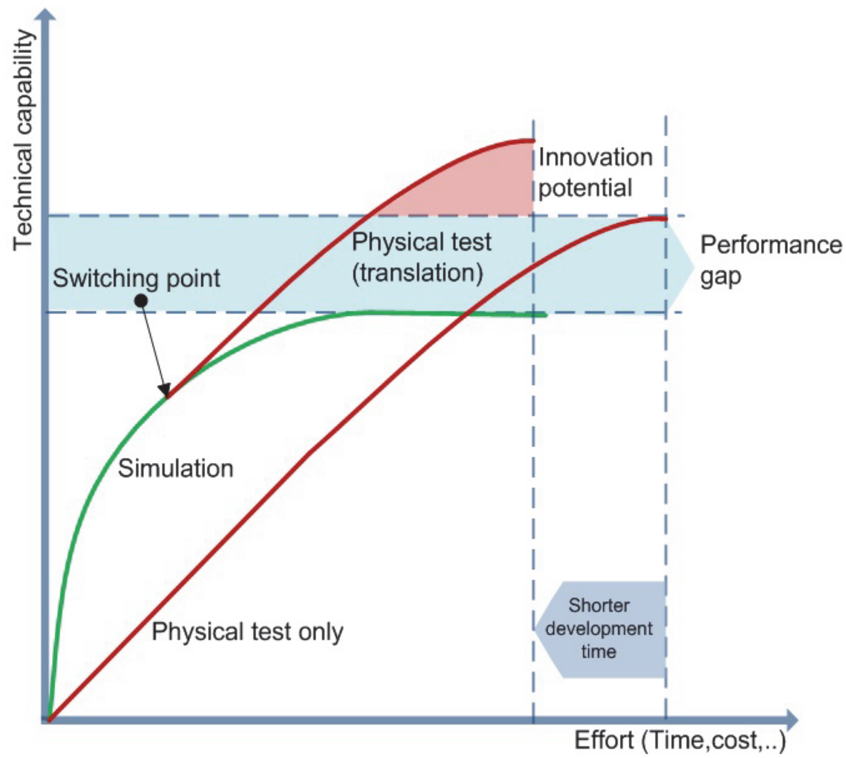


Figure 4.6: Combining physical test and simulation to deliver innovation. Adapted from (Van Der Auweraer & Leuridan, 2005)

With simulations only, the available technical capability can be used very fast and the development time is shortened. With physical tests solely, much more effort is needed to use the available engineering capacity, but uncertainties are firmly eliminated at each attempt (Gerber, 2009). Switching from simulations to physical tests by exploiting a simulation's initial results considerably reduces the effort to benefit from an organisation's overall technical capability. It also opens new avenues for the validation and exploration of product behaviour and further innovation. The optimal combination of simulation and physical test not only provides better system performance exploration, refinement and certification but continually reduces development time, strengthens virtual prototyping and finally opens new solution spaces for innovation. Liu et al. (2013) report on similar findings. However, the simulation-to-test switching point can be difficult to determine in practice because current virtual product representations mainly consider geometry and materials and they are strongly oriented towards production rather than product behaviour in the physical environment. This is typically due to a limited application of behavioural descriptions of components when assessing system functions under diverse circumstances, despite advances made in Functional DMU (Enge-Rosenblatt et al., 2011; Fukuda, Lulic, & Stjepandic, 2013; Schneider et al., 2010; Stark et al., 2011; Vosgien, 2015). Indeed, correlation between design activities and virtual and real system testing are poorly established and the implications of the testing results on the corresponding CAD/CAE-simulation models have rarely been addressed up to now (Liu et al., 2013; Riel & Brenner, 2004; Vosgien, 2015). It is therefore necessary, as a first step, to provide a means of linking these specific types of information and transactions within existing PLM contexts. In addition, any attempt to do so, and in the process further leveraging the combination of physical tests and simulations for product refinement, should stem from current industry practices, paradigms, and information technology infrastructures (see section 4.3).

In view of this, a critical aspect to consider regarding the testing and refinement phase is planning for prototypes (Camburn et al., 2015a; Hammon et al., 2014; Thomke, 2008; Ulrich & Eppinger, 2012). This planning stage can be divided into four steps. The whole process as described in Fig. 4.7 aims at optimizing the lessons learned that result from testing prototypes.

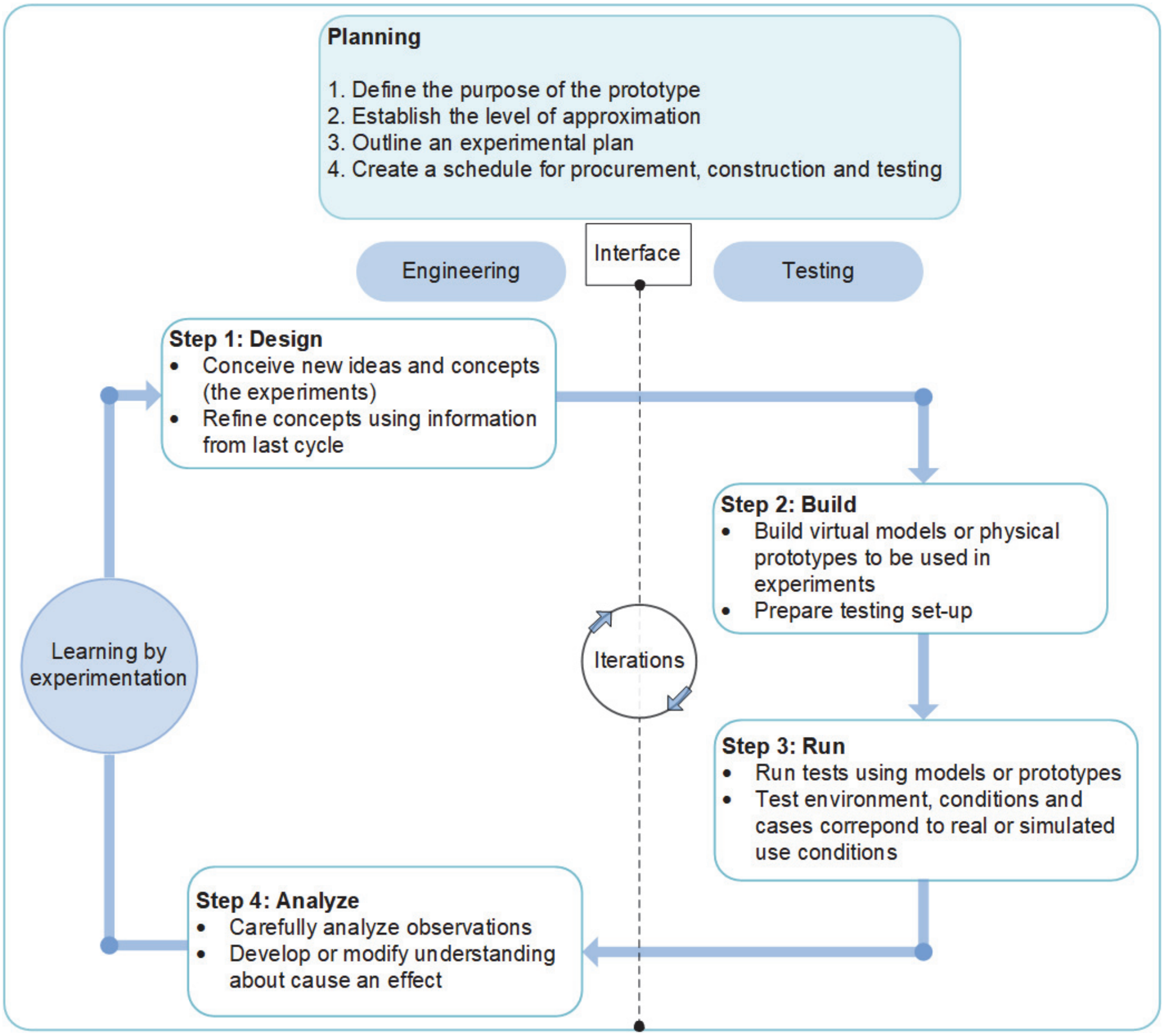


Figure 4.7: Experimentation as a four-step iterative cycle. Adapted from (Thomke, 2008)

When considering a testing team, the challenge lies in managing interfaces with other value streams. Indeed, Thomke (2008) states that how firms link experimentation and testing activities to major process phases, system stages, and development tasks is an essential part of effective management practice. As a practical example, McSorley (2014) identifies difficulties in ensuring that information collected during development testing is efficiently shared with designers and made available for reuse in future development projects. In a collaborative project with an aerospace manufacturer which studied the information collected in 231 Test Event Reports (TER), it was found that the varying format and structure of information can complicate the reuse of the test information for the design of subsequent products by making it difficult for designers to quickly access similar reports and by then, limiting their awareness of past test initiatives. To address this interfacing problem, the next section will examine how the evolving product can be concurrently represented in the context of both design and testing activities by drawing on parallels with the integration of design and manufacturing activities. Following this, the strategies developed will be applied to a practical case study.

4.3 Digital product information for prototyping during the PDP

Over the last decade, there have been important changes in the way engineered products are created, built, serviced and disposed of in order to meet both customer needs and regulation requirements. This is not only characterized by the advances in computer support technologies (Durmuşoğlu & Barczak, 2011; Hines et al., 2006; Waurzyniak, 2008), the on-going shift towards the Virtual Prototype (Coyle & Paul, 1997; Gausemeier et al., 2011; Hirz et al., 2013; Lorisson, 2010; Ottosson, 2002; Radkowski, 2011; Wang, 2002), and the now established end-to-end cross-functional use of Digital Mock-Ups (DMU) through the evolution from classic DMU to Functional DMU (FDMU) and furthermore industrial DMU (iDMU) (Drieux, 2006; Enge-Rosenblatt et al., 2011; Garbade & Dolezal, 2007; Herlem et al., 2012; Lazzari & Raimondo, 2001; Mas et al., 2014). As defined by Coyle and Paul (1997), a virtual prototype is an integration of data from various sources that define the total product and its environments. It provides superior means of visualizing any aspect of product design, behaviour, its fabrication and assembly and the environment it will be used in. Wang (2002) gives a similar definition of the virtual prototype, equating it to the digital mock-up for the purpose of being visualized, analysed and tested from product lifecycle aspects such as design, engineering, manufactring, service and recycling as if on a real physical model. Wang (2002) and Ottoson (2002) distinguish virtual prototyping (the construction and testing of a virtual prototype) from virtual reality (VR) which allows the user to become further immersed and to experience a strong sense of feeling and presence.

The important changes in the way engineered products are created, built, serviced and disposed of are also related to the actual development process of new products (Stark, 2015; Ulrich & Eppinger, 2012; Wheelwright & Clark, 1992), which entails critical principles and practices such as Concurrent Engineering (CE), cross-functional collaboration (Kim & Kang, 2008; Mas, Menendez, Oliva, & Rios, 2013b; Prasad, 1996), process parallelization and integration (Eversheim & Schulten, 1999; Fortin & Huet, 2007; Terwiesch et al., 2002), Configuration Management (CM) (Watts, 2012) and, change management (Jarratt, Clarkson, & Eckert, 2005). These practices are industrial responses to the ever changing and competitive marketplace. The amount and nature of informational transactions among participants have changed in a remarkable manner and the common virtual representation of the product is now made up of large quantities of detailed and interrelated data. This product-centric information should be accessible from several locations and also be adapted for different domains of expertise by leveraging flexible Product Structure Management (PSM) strategies (Svensson & Malmqvist, 2002). The information must continually remain available in order to support the product development process with the aim of reducing waste, the current and future development costs, time, and quality issues. In such a context, product lifecycle management (PLM) is regarded as the ultimate support solution for product development (Sääksvuori & Immonen, 2004; Stark, 2015; Waurzyniak, 2010) and is implemented by many companies to try to meet these challenges. Within the current industrial context, valuable product information is scattered throughout various functional areas in the company. The PLM challenge is therefore to provide an information and process driven approach to implement the integrated cooperative and collaborative management of product data, throughout the entire product life (Fortin & Huet, 2007; Liu, Zeng, Maletz, & Brisson, 2009; Terzi, Bouras, Dutta, Garetti, & Kiritsis, 2010). Much remains to be developed to fully implement this vision.

Literature review and workshops with industrial partners from previous practical action research (Toche, Huet, McSorley, & Fortin, 2010; Toche et al., 2012) as well as this thesis participatory action research structured focus groups (transformational workshops campaign) have led to the following observations when it comes to the testing and refinement phase of the Product Development Process (PDP):

- The required physical tests and procedures and derived as-tested product structures (or bills of materials) are not systematically connected to the as-designed structure and therefore their proper configuration management is not possible within the PLM environment;
- Consequently, hardware testing transactions and prototype information tracking are not addressed within common PLM solutions.

Figure 4.8 is a detailed view of Fig.4.4 presented in section 4.2 which graphically showed the numerous physical prototypes that can be built and tested during the development of a complex aerospace system. It is possible to see additional examples of the various reasons for building physical prototypes during an aerospace PD, as explained in section 4.2.

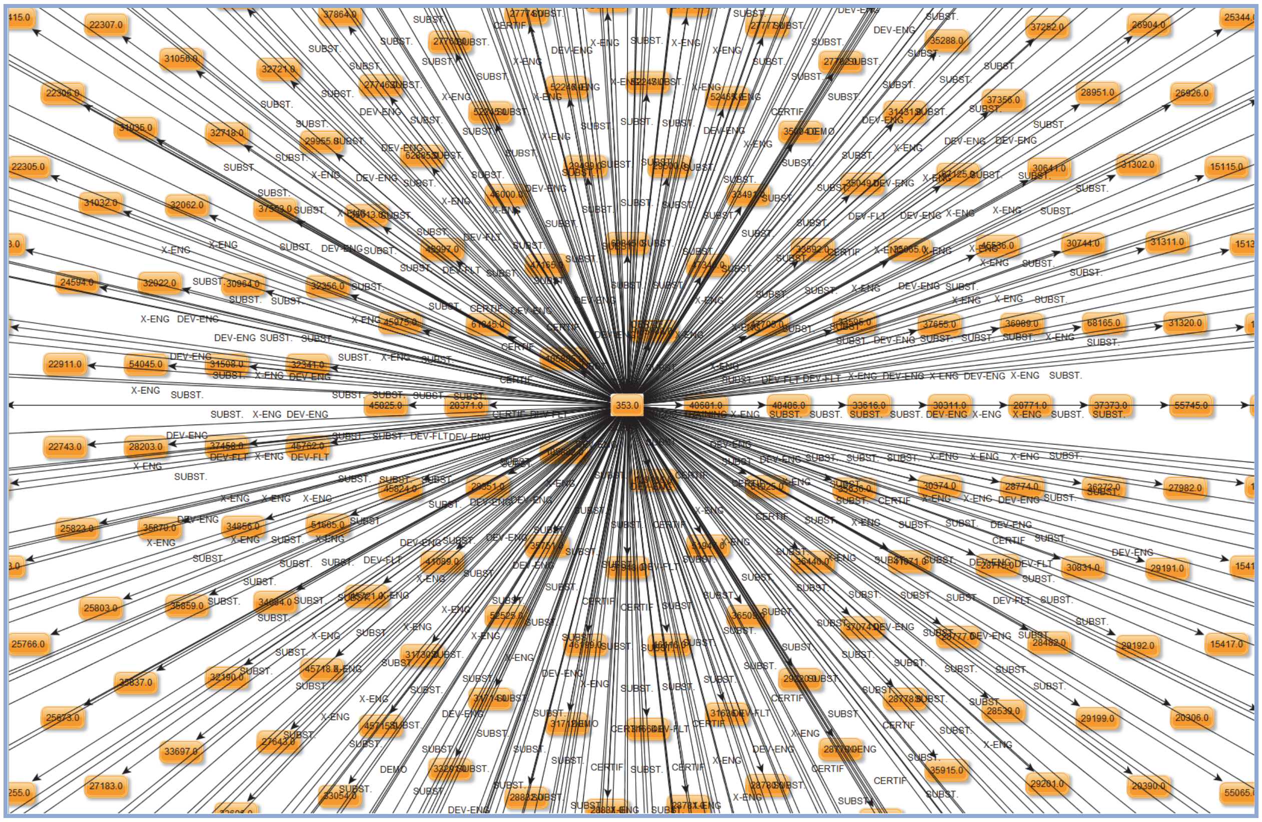


Figure 4.8: Experimental builds during the development of a complex aerospace system (detailed view)

A leaf node in the graph represents a build which is aligned with a unique as-designed (design intent) configuration (not represented) and which, at the same time, contains all the approved approximations and deviations made for the purpose of the test. The prototypes also involve manufacturing processes and transactions because they are physically built. Another aspect not represented on the graph (to ease readability) is the fact that each build may be versioned several times as a mean to document minor changes done while testing the configuration. Performance metrics and run times are accumulated both at the build and the detail itinerant hardware component level to comply with design substantiation requirements and inform future design decision-making. These industrial prototyping and testing aspects do not exist in PLM solutions, which may result in disconnected value streams, scatter and waste.

The goal is therefore to provide a framework that can support the management of prototyping and testing information in a PLM perspective. The next section characterizes information in the context of PLM by discussing some critical concepts regarding digital product information and DMUs in the PDP. A scenario is then presented regarding a framework based on a configurable product model and complementary product structures where information from prototyping and testing activities could be mapped and merged with design activities in order to maintain product configuration and satisfy stakeholder needs in a cross-functional setting.

4.3.1 Characteristics of information in PLM

The notion of product data and a new perspective on the DMU are first presented in this section in order to introduce the nature and type of information typically managed during the PDP. Product Data Management (PDM) in combination with Manufacturing Process Management (MPM) are then discussed more extensively as they represent the main infrastructure supporting the information sharing process.

4.3.1.1 Digital product information and the DMU

A digital mock-up (DMU) corresponds to the basic idea of creating computer models for all relevant aspects of the product in development and to analyse them in context with the main purpose of reducing the time and cost related to the construction of real prototypes. DMU can be defined as a digital 3D representation of a product/system (including manufacturing system) together with its product structures and attributes (Dolezal, 2008; Gausemeier et al., 2011; Hirz et al., 2013), all of which make up the so-called *digital product information*, which in turn is made up of *product data*. This product data, being all informational entities related to the product, can be clustered into three types (Sääksvuori & Immonen, 2004):

- *The specification data* technically describe the physical, logical and functional properties of the product. It is through these descriptions that stakeholders transmit their expertise. Sketches, CAD models, drawings, FEA, NC files, test plan files, performance data, etc. are well known examples;

- *The lifecycle data* identifies the status and maturity of product information. It is useful for managing the evolution of product information throughout the product development and its lifecycle;
- *The metadata*, so called "data about data", serves to locate, identify, trace, retrieve and eventually describe the data for an efficient use of the embedded knowledge.

By collecting and structuring such an array of data, the DMU can also be considered as playing a core supporting role for three typical dimensions of interest in PDP transactions, namely technical, communication, and management. This supporting role is illustrated in Fig. 4.9, which includes the types of information organised within the DMU, as well as the processes which it supports. For example, the Data & Design Quality Assurance process, part of the technical dimension, uses the DMU as a core reference to demonstrate compliance to the quality metrics. The DMU itself does not manage the process.

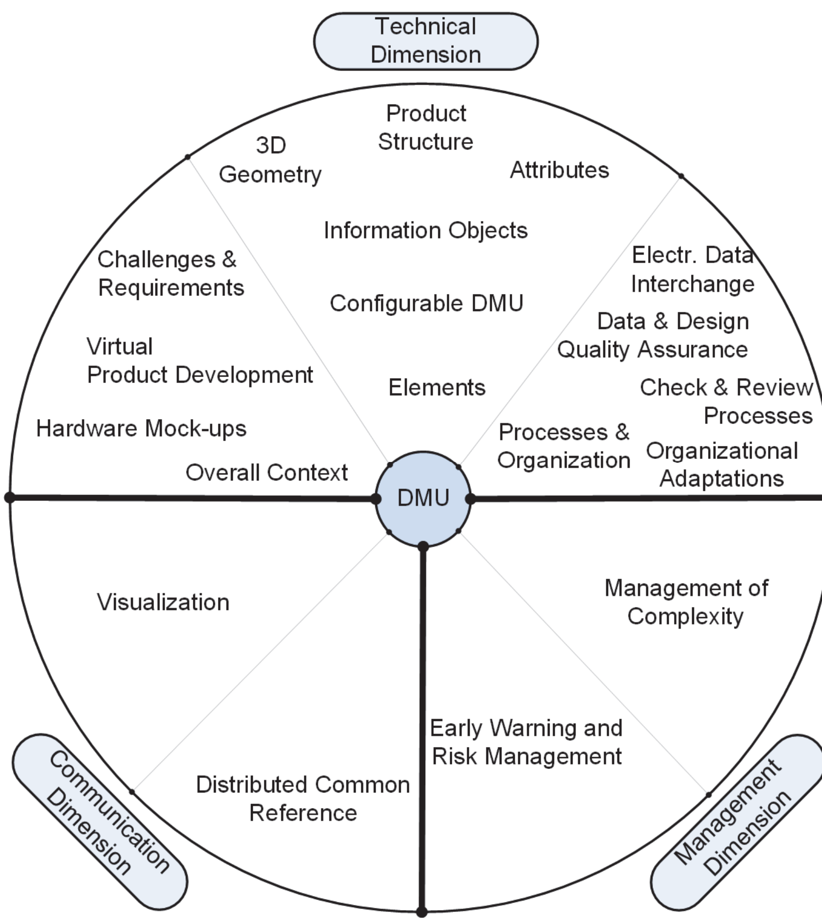


Figure 4.9: Three dimensions of DMU support. Adapted from (Dolezal, 2008)

As the DMU was extended to enable product behavioural aspects i.e Functional DMU (FDMU) (Enge-Rosenblatt et al., 2011; Fukuda et al., 2013; Schneider et al., 2010; Stark et al., 2011; Vosgien, 2015) and manufacturing/assembly processes and resources i.e. industrial DMU (iDMU) (Mas, Menéndez, Oliva, Gómez, & Ríos, 2013a; Mas et al., 2014; Menéndez, Mas, Servan, Arista, & Ríos, 2013), the boundaries of the concept may sometimes appear unclear in the literature (Pinquié, Rivest, Segonds, & Véron, 2015). This can be resolved by understanding the DMU as described here, which is the backbone of the enabled behavioural simulation layer and collaborative engineering connectivity.

From a product structuring standpoint, Van den Hamer and Lepoeter (1996) described the *non-isomorphic* hierarchies model in which each domain view has its own internal hierarchy with the views being optionally linked by equivalence relationships. This model is contrasted with the level-by-level model where there is only one consolidated hierarchy which is expected to satisfy requirements from multiple views. Figure 4.10 illustrates the contrast.

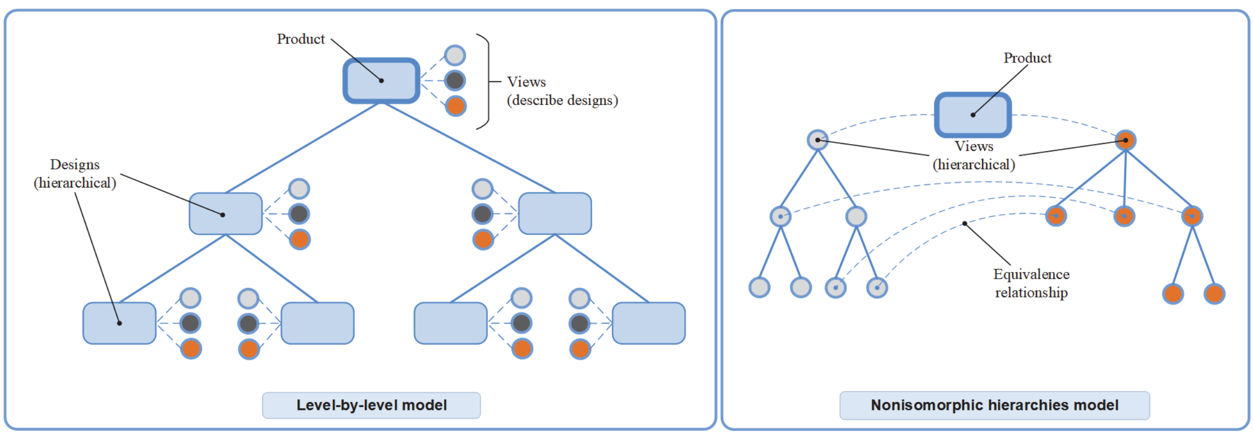


Figure 4.10: Level-by-level vs. non-isomorphic hierarchies models. Adapted from (Van Den Hamer & Lepoeter, 1996)

Each model has its own set of advantages and disadvantages. As it will later be discussed, complementary information structures for example, by using a *non-isomorphic* hierarchies model to synchronise engineering data with manufacturing realities, present the advantage of allowing as-built DMUs to exist (Fortin & Huet, 2007; Huet et al., 2011; Toche, Huet, & Fortin, 2011). This advantage is also available from iDMU (Mas et al., 2013b; Menendez et al., 2012) which appears to be using a level-by-level model to gather and consolidate the product, processes and resources information on a single backbone reference for collaborative engineering.

To complement these high level concepts on digital product information, the more specific topics of geometry and Bill of Materials (BOM) are discussed below as they leverage product data for an effective implementation of embodiment, prototyping and manufacturing activities. Also, the notions of attributes and configurable DMU are detailed as they significantly contribute to data presentation, selective retrieval, data management and traceability throughout all product development activities.

Geometry

As basic specification data, 3D models provide an insight into a component's shape, functions, and the design intent. While not necessarily representing manufacturing tolerances or operational deformations, 3D models are the closest digital replicas of the parts to be produced. Therefore, they serve as the main three-dimensional visual references for all participants. The level of detail of the models depends both on the lifecycle stage and the objectives and requirements of the activity under consideration. Similarly, geometry will vary in terms of being exact or approximate, as well as having reduced data volume or not.

Bill of Materials (BOM)

The Bill of Materials (BOM) represents a particular way of aggregating and presenting product data by disclosing hierarchical and logical dependencies among parts as well as relevant objects. The BOM, effectively a product structure reflecting a certain domain, facilitates access to product data by organising it and adding complementary information, related to the field of expertise of the relevant stakeholder as well as the lifecycle maturity of the data itself. Two BOMs are frequently encountered:

- A*s-designed* structural view BOM, which is typically a functional decomposition of the product, communicating its systems arrangement via interface control objects. It is the engineering BOM (eBOM) and facilitates access to design data of assemblies and parts;
- *As-planned* structural view BOM, which reflects how the product is to be manufactured and assembled from a process planning or manufacturing perspective. It is the

manufacturing BOM (mBOM) and facilitates access to manufacturing resource data and process plans.

Depending on the lifecycle approach applied in the company, many other representations could be relevant (Huet et al., 2011), such as a maintenance BOM or a quality BOM (Brissaud & Tichkiewitch, 2001; Männistö et al., 2001). In this thesis, the concept of an "*As-tested*" product structure, previously proposed in (Huet et al., 2011; Toche et al., 2012), will be developed to reflect the specific needs of testing and prototyping activities, which, as mentioned previously, are difficult to represent, control and track in current PLM implementations. Figure 4.11 illustrates the various product structures and BOM requirements that were captured following the industrial lean PLM transformation structured focus groups (see chapter 3) and then arranged using qualitative coding (Strauss & Corbin, 1990). These BOMs are aligned in the display with the corresponding lifecycle phases while encapsulating the variation from one BOM to another in a simplistic product structure. As-required structure is not represented in the display.

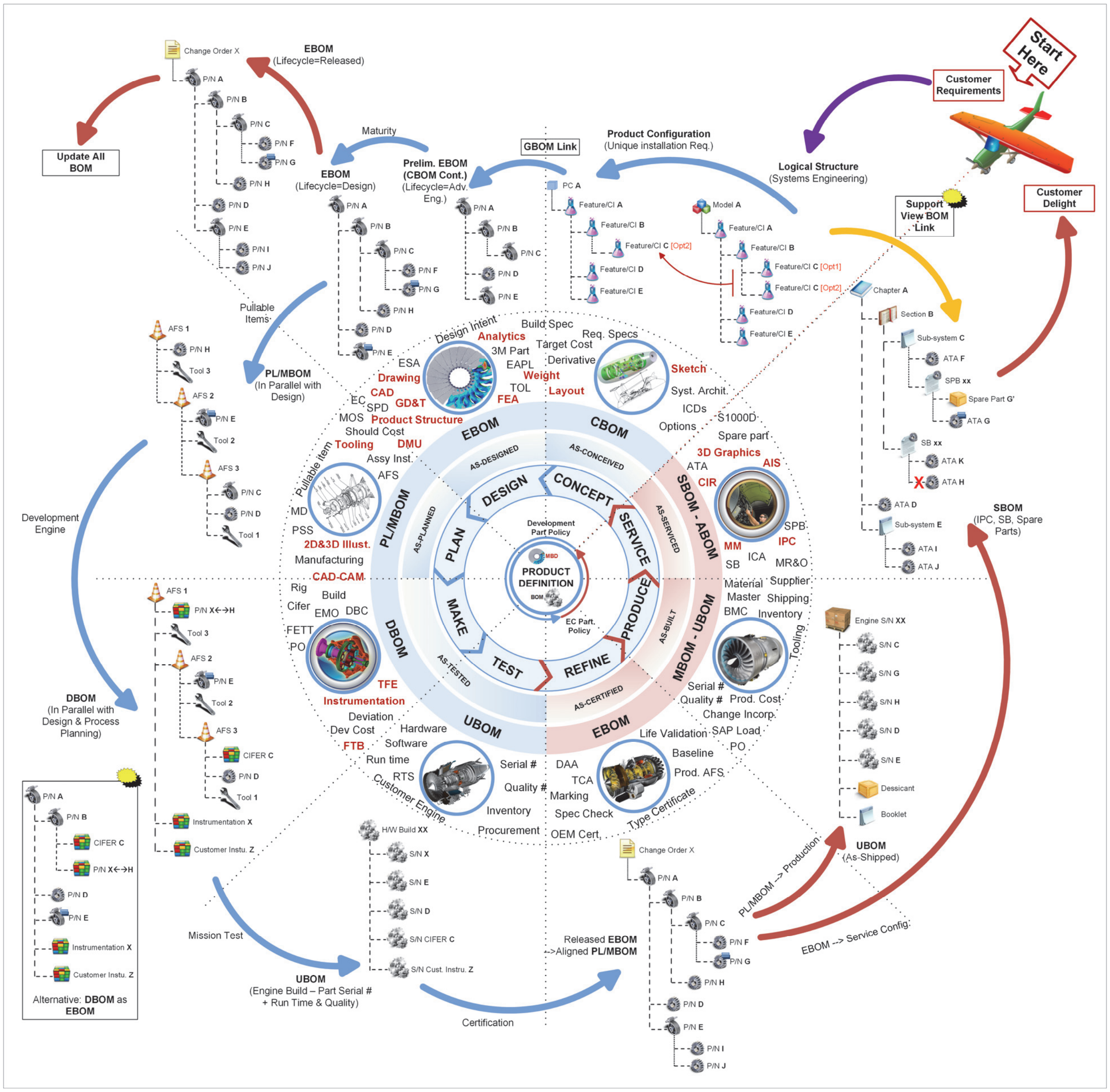


Figure 4.11: Requirements for Product Structure and Bill of Materials progression

The difference between *as-tested* development BOM (dBOM) and unit BOM (uBOM) as proposed in this thesis should be elaborated and clarified:

- Development BOM (dBOM) represents the definition of a prototype including approximations and deviations from the target reference design. It is used to describe and subsequently record the actual hardware definition installed in a development build. All differences between the eBOM configuration reference datum and the dBOM are documented and approved by design engineering. dBOM needs structure or feed from process planning because it is physically built. Successive builds (dBOM versions) then continually align with maturing eBOM and up-to-date manufacturing and assembly strategy;

- Unit BOM (uBOM) is the manifestation of a physical product instance with the actual serial numbers of the installed components. Sometimes referred to with *as-built* structure, it contains information related to the physical identification of the hardware build part, its current location (installed/in-store), the run time and product build history, its health quality and usability for a development test mission. Development build configurations evolve as versions of the uBOM which represent the physical product as modified. As-delivered production instance may also be recorded with uBOM, which will then become the starting point for the *as-maintained* BOM.

Attributes

Attributes include all the metadata and lifecycle data for effective information management and distribution, and are key enablers for traceability and concurrent work. The relationships between the DMU data, metadata and geometry are shown in Fig. 4.12.

The product structure is considered a combination of data and metadata, as it is the result of a dynamic construction leveraging the links between items as well as the user's context and the status of attributes.

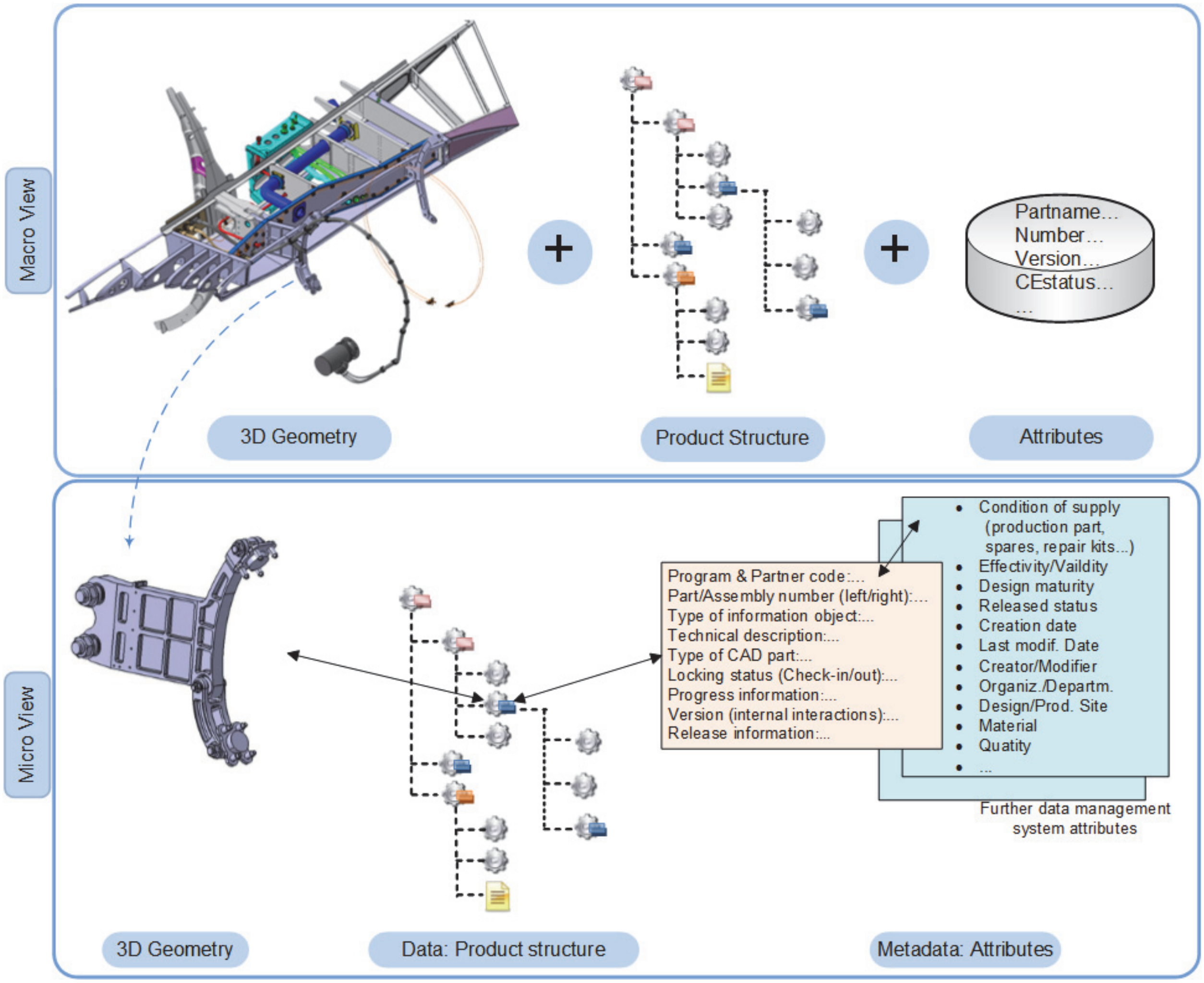


Figure 4.12: Relationship between geometry, product structure data and metadata on a simplified example

Configurable DMU (CDMU)

A Configurable Digital Mock-Up (CDMU) introduces Configuration Management (CM) to the DMU. CM is a management process ensuring that:

- the different configurations of a product structure are properly available and controlled;
- products conform to the design and documentation governing their development and production;
- documentation is controlled and reflects the latest, approved version;
- end users will have the capability to obtain and maintain exact delivered products.

(EIA-649-B, 2011; Eigner & Fehrenz, 2011; Watts, 2012).

The aim of a CDMU is to use integrated effectivities (Watts, 2012) to provide a complete digital product in any variant for any stakeholder, including designers, and regardless of the design phase (Dolezal, 2008). A CDMU controls iterations of the product data from design, manufacturing or any other actor working via the DMU. The CDMU is of a particular importance in this study because it is through this that multiple design configurations are built/tested in parallel and physical instances can be reflected and tracked for further analysis and refinement. CDMU as described here should be understood as equivalent to the configurable product structure (Eigner & Fehrenz, 2011; Erens & Verhulst, 1997; Männistö et al., 2001; Svensson & Malmqvist, 2002; Tiihonen et al., 1998; Wortmann, Muntslag, & Timmermans, 1997) when 3D representation is of lesser importance.

4.3.1.2 PDM and MPM at the heart of the PLM infrastructure

PDM is an essential enabler for PLM (Sääksvuori & Immonen, 2004; Stark, 2015) since it includes key functionalities related to the virtual product such as data vault and document management, structure and configuration management, data sharing and exchange, pre-visualization and notifications. PDM also supports key activities such as approvals or engineering change processes. Parts and specification documents in PDM systems, such as CAD models, pdf documents, MS Excel spreadsheets, or other type of objects define the form, fit, and function of the product and its components. This is supported by a framework using the DMU as the common representation of the intended physical product.

As far as manufacturing is concerned, the MPM platform bridges the worlds of engineering and production by focusing on the manufacturing process definition of the product (Huet, Fortin, McSorley, & Toche, 2010; Huet et al., 2011). It takes advantage of the complementary information structures developed by design and manufacturing engineers, being the eBOM (as-designed product structure) and mBOM (as-planned product structure) respectively, and full CAD representations to converge towards an optimal parallelization of design and manufacturing processes through the digital collaborative environment. MPM plays a central role in concurrent engineering, facilitating the evolution from a digital to physical representation of the product (Fortin & Huet, 2007). The focus here concerns the way in which MPM can facilitate the evolution of the spatial and physical embodiment of the product, as well as the transactions necessary to control the evolution of the related product data while meeting requirements for the verification and validation process. In concrete terms, this represents the transition from the 3D geometry to manufacturing simulations and product verification and validation, then from product data to production data such as manufacturing process plans and resources.

4.3.2 Complementary product structures for set-based prototyping

Based on advances in DMU technologies and simulation (FDMU, iDMU, Virtual prototype, etc.), real life assessment in modern engineering is now possible in both physical and digital worlds. As such, the cross-functional interaction spans digital modelling and simulation as well as physical construction and testing, as long as a physical test is necessary to explore a phenomenon that is not otherwise possible with a proven simulation-based experiment. Learning by experimentation, on the short term, supports design convergence. On the long term, it spearheads the core organisational learning system at the root of set-based design methodologies (Ward & Sobek, 2014). According to the specific processes and the amount and nature of information that can be generated, some specialized tools exist to support prototyping and testing during the aerospace product development. However, these tools retrieve engineering product information from dedicated systems in a transactional mode and are therefore rarely part of an integrated value stream or feedback iteration as discussed above. The result is a situation where the development and test information system supports the construction and test of multiple prototypes but all relevant information pertaining to them remain scattered, reducing upstream and downstream visibility. This section focuses on proposing a strategy to handle multiple digital prototypes (alternatives) in the form of Product Structure/DMU configurations that also enables synchronization with simulation, physical prototyping and testing information.

4.3.2.1 Management of complementary product structures

As the design of the product evolves, designers produce a functional view of the specific end item, namely the *as-designed* product structure (or eBOM) which is part of a design framework that typically includes the DMU and eventually FDMU/virtual prototyping. Once a certain level of design maturity is achieved, the testing team collaborates with design to define the physical prototyping strategy, including certain aspects of fabrication. According to the level of approximation, the prototyped parts are often not identical to as-designed models since modifications are done for instrumentation reasons (e.g. additional holes for passing instrumentation wiring, or modifications for fixing temperature probes, strain, pressure and fuel gauges) or simply because the scope of the test is limited to a particular behaviour of the component i.e. partitioning and isolation (Camburn et al., 2015a). This usually results in distinctly identifying the modified definition while maintaining the relationship with the original design engineering definition. Furthermore, the need for parallel, yet distinct, product models leads to the complexities in managing the interface between design and testing activities as previously observed. It is in this context that the use of complementary product structures is proposed as a framework to ensure coherent relationships between the as-designed and as-tested product structures.

To facilitate their work, the testing team must manage, in parallel, complementary product structures mirroring and following the as-designed ones. These *as-tested* BOMs represent a physical instantiation of the product that will be tested. The general information concerning a manufactured and assembled test prototype is organised in a test plan previously validated both by the design and testing teams. The test plan, the procedure for the execution of the test, the collected run times, design performance metrics and the overall test results represent the main outcomes of the testing activities. These results will be attached to the complementary structure and tracked back to the requirement (V&V) to refine the product.

The modifications that lead to as-tested arrangements which are adequate for tests are not dissimilar from those necessary to build and maintain the mBOM, which is usually deployed through a manufacturing process management (MPM) module in PLM. Indeed, manufacturing, or as-planned, product structures result from the manufacturing strategies and are rarely identical to as-designed structures. These complementary design and manufacturing structures remain interconnected through the MPM module which may implement the notions of (Fortin, Toche, McSorley, & Huet, 2010; Huet et al., 2011):

- *Equivalence links* to relate a part's iteration in the mBOM to the equivalent part in the eBOM, ensuring conformity and traceability;
- *Occurrence links* to relate the position of equivalent parts within the different BOMs, enabling identical 3D visualization of the mock-up;

- *Reference links* to propagate changes when a manufacturing part does not have a strict equivalent in the eBOM.

These links are built in a *non-isomorphic* hierarchies model (Van Den Hamer & Lepoeter, 1996) in order to strengthen the synchronisation between the views, allow for contextual 3D visualisations and to support effective change propagation in heterogeneous domains.

While current implementations of MPM focus on the relationship between eBOMs and mBOMs, it is proposed that the same strategy can be used to manage other complementary product structures, such as the *as-tested* product structure. The use of a complementary structure, rather than a monolithic structure, also facilitates the addition to the as-tested structure of components specifically designed for the tests (for example instrumentation and test rigs) as well as the efficient reuse of portions of as-tested structures previously developed for similar test cases. Assuming that as-tested structures are deployed and remain connected to the as-designed structure, via the links discussed above, Fig. 4.13 illustrates how each physically built instance is reflected and tracked by both the Design and the Development & Testing groups. The figure features a simplified example that is used to ease readability and is centred upon a conceptual end-item labelled A which includes two parts, C and D, and an assembly B composed of two parts, B1 and B2.

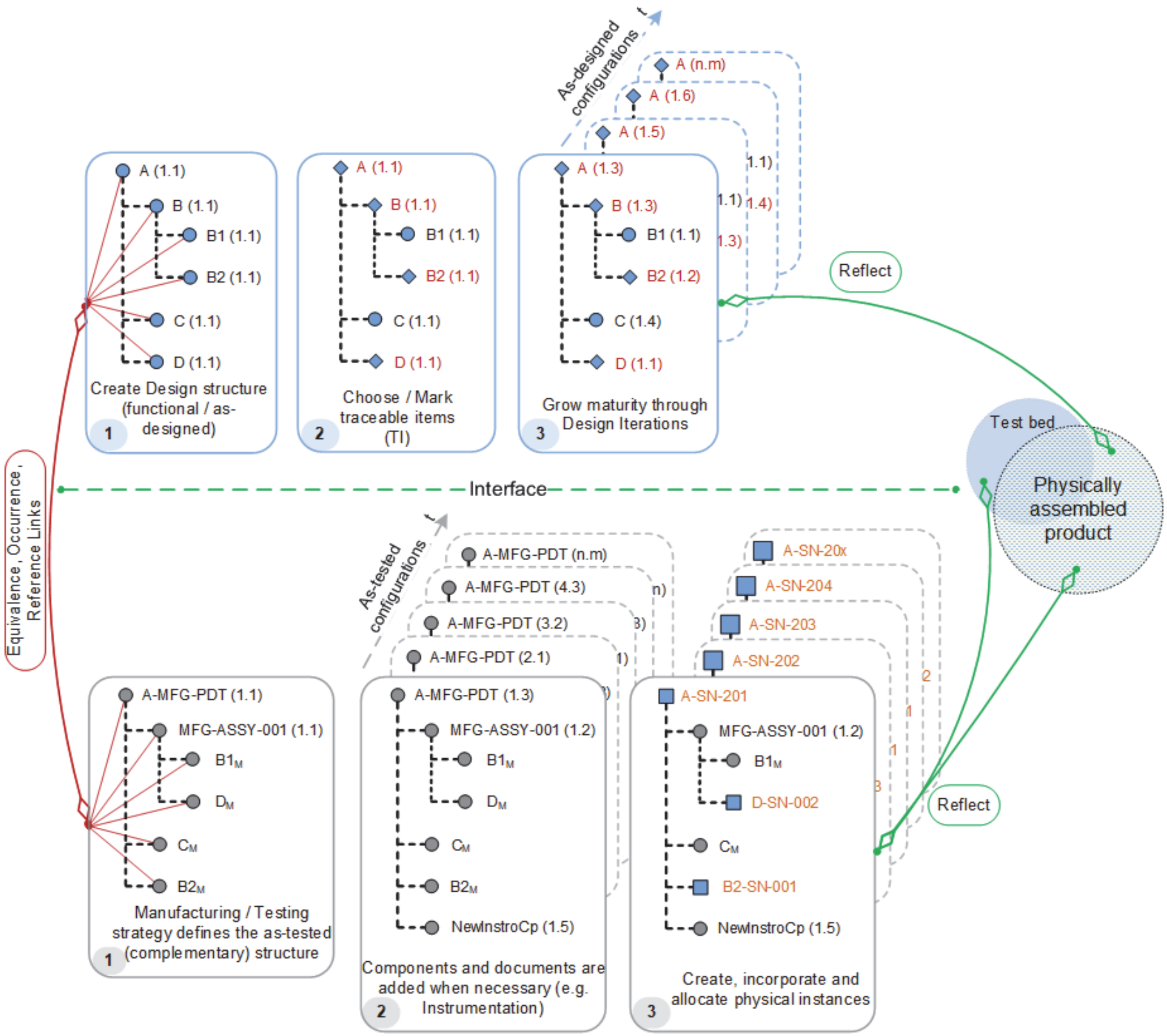


Figure 4.13: Complementary and configurable information structures - a diagrammatic analysis

The creation and management of the linked as-designed and as-tested structures consists of:

- Selecting and marking the relevant parts that have to be tracked throughout the lifecycle. These parts are designated as traceable parts and the trace code can be a serial number, a lot number or a combination of both;
- Maintaining configurations based on change effectivity as maturity is evolved and more design variation is added – this works as extending the structure (150%) to include the new version alternatives, which can later be filtered using the selected effectivity expressions;

- Creating instances from filtered configurations: an instance, which requires a serial number, corresponds to an existing physical part, such as one manufactured for tests, at the available level of maturity;
- Incorporating lower level instances: incorporation is the date when a new configuration associated to an end item instance takes effect. The method is used to track on-going configuration changes to an end item instance that has previously been tested;
- Allocating instances[3]: allocation is the process of associating specific end item instances and serialized parts to each other. In fact, a top-level end item instance is not completely defined until all of the serialized parts and end item instances are associated with it.

As illustrated in the figure, a prototype could therefore be built and tested from a specific configuration of the end-item while design iterations are continuing to evolve. To do so, instances of the parts are generated from the captured configurations and identified by their serial numbers or lot numbers as provided by the suppliers or the teams on the shop floor. These instances are allocated to form the complementary structure (as-tested) reflecting the physically assembled prototype. Since the structure remains linked to its as-designed version, traceability regarding all the approximations made while prototyping and testing is enabled. As the serial and lot numbers are identified, the physical parts are also tracked. This methodology can also be applied when all parts and documents have reached the release status. As a result, each tested, produced, or delivered instance of the end-item is fully traceable.

4.3.2.2 Research-based case study (Pilot Simulation I)

The following example is drawn from a master's level aerospace system's integration project completed each year by a team of 12 to 16 students at Polytechnique Montreal. This project is one of a kind because it is still probably the only one in the world allowing students to simulate real life aerospace engineering practices based upon:

---

[3] Not to be confused with an occurrence, an instance corresponds to the materialisation of an artefact item and therefore identifies a unique physical part, whereas the occurrence identifies the presence and unique position of a part within the digital mock-up.

- Real life technical documentation and product development process manuals, cleared and shared by the supporting aerospace companies i.e. Bombardier Aerospace, Pratt & Whitney Canada and Bell Helicopter Textron Canada;

- Advanced CAD-PDM-MPM tools with the courtesy of Dassault Systemes and Parametric Technologies Corporation;

- Close advising and monitoring from Quebec area aerospace industry experts in Project/Program Management, Design, Engineering, Prototyping & Testing, Manufacturing, Configuration Management and FAA/TCCA Certification.

The project scenario features a development team involved in a significant engineering change consisting of the design of a new pylon to install a PW305A engine from Pratt & Whitney Canada on a Bombardier Aerospace CRJ-700 regional jet. The retrofit provides a new variant of the aircraft and the change necessitates re-establishing compliance with aviation regulations via certification tests and detailed analysis of the pylon's main subassemblies, including the primary and secondary structures, along with the bleed air, fire extinguishing, fuel, hydraulic, and electrical systems. One of the most critical components is the forward engine mount, which forms part of the pylon's primary structure and for which the FAR25 certification regulations apply. As for any regulated aircraft design process, prototype planning and development is performed concurrently with the creation of the General Compliance Plan (GCP) and the Certification Plan (CP), which help define the scope and methodology of the required tests.

In the context of this project, the forward engine mount is the design artefact to be physically prototyped and tested. The prototype is used to validate the role, functionality and look and feel dimensions; however the emphasis is placed on verifying the validity of the structural analysis completed on a virtual prototype. In this context, it will be demonstrated how complementary product structures can practically ensure the coherence of the as-designed and as-tested product structures of the forward engine mount as they evolve within the project.

The role of forward engine mount is to support the engine in take-off, flight, and extreme crash conditions; to transmit the engine thrust to the aircraft; and to form a barrier which defines the fire zone. The implementation involves the selection of an improved titanium alloy and the structural design itself. The look and feel is of limited importance for this structural artefact. The as-designed mount assembly in the context of a configurable DMU is displayed in Fig. 4.14.

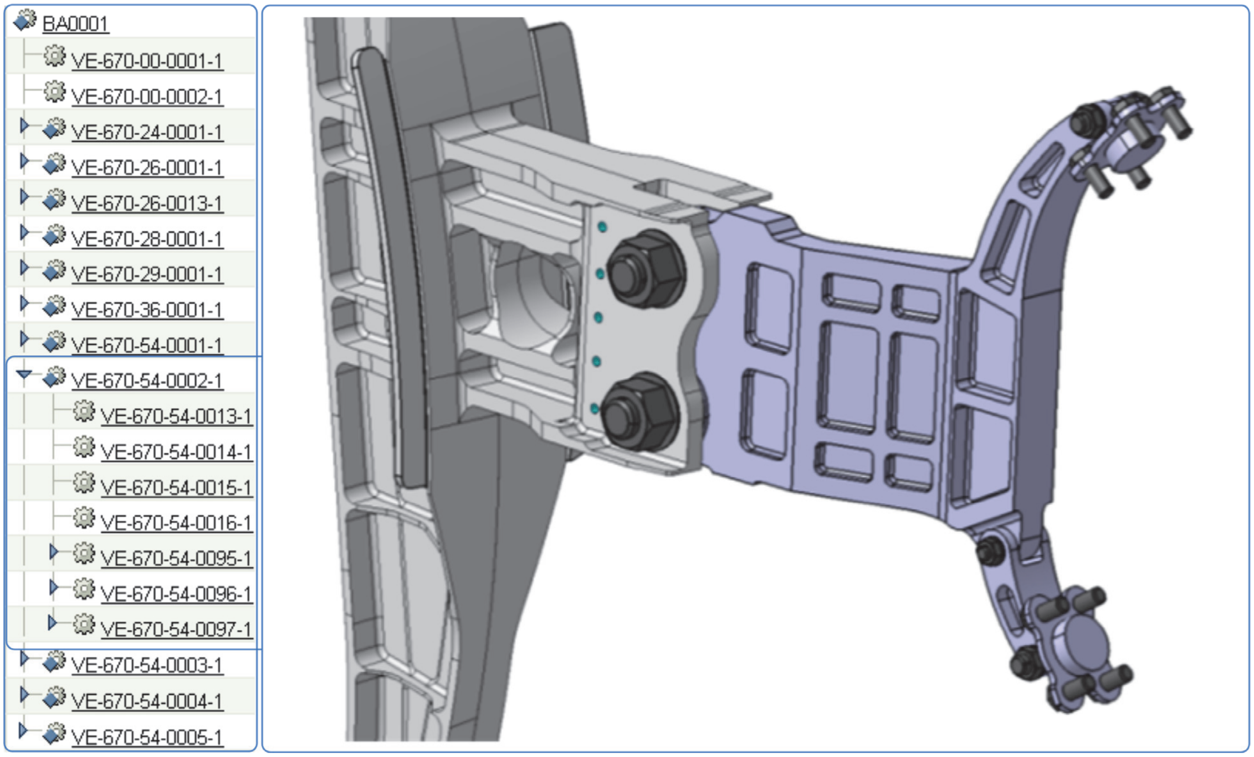


Figure 4.14: "As-designed" forward engine mount structure and corresponding 3D representation

At this stage of the design captured in the figure, the component has been designed to survive severe load cases, while also undergoing weight reduction efforts. An initial optimization of manufacturing time and cost has also been completed, all supported through the use of virtual prototypes. The engine mount is also an interface component since it is the link between the installed engine and the fuselage frame. The connecting interface with the engine must be as flexible as possible so as to facilitate engine installation and to withstand phenomena such as thermal expansion. The mount therefore features both an upper and lower pad and a mount link, enabling the proper degrees of freedom. The hardware labelled C in Fig. 4.15 includes three bearings to allow pivoting motion as well as titanium fasteners to strengthen the connections.

In conformity with the functional view of this end-item, designers have provided the displayed as-designed BOM. Assemblies and components are defined by following a strictly functional logic, as demonstrated by subassemblies B, C and G, which are made up of connectors grouped by similar functional roles. Note that the component parts of the three listed assemblies are not displayed within the BOM in Fig. 4.15 in order to ease readability. As the prototype must be manufactured and tested, it is necessary for the project participants to manage the complex transition from virtual to physical prototyping. The required complementary product structures to support this process will be discussed in terms of both the as-planned (mBOM) and as-tested structures.

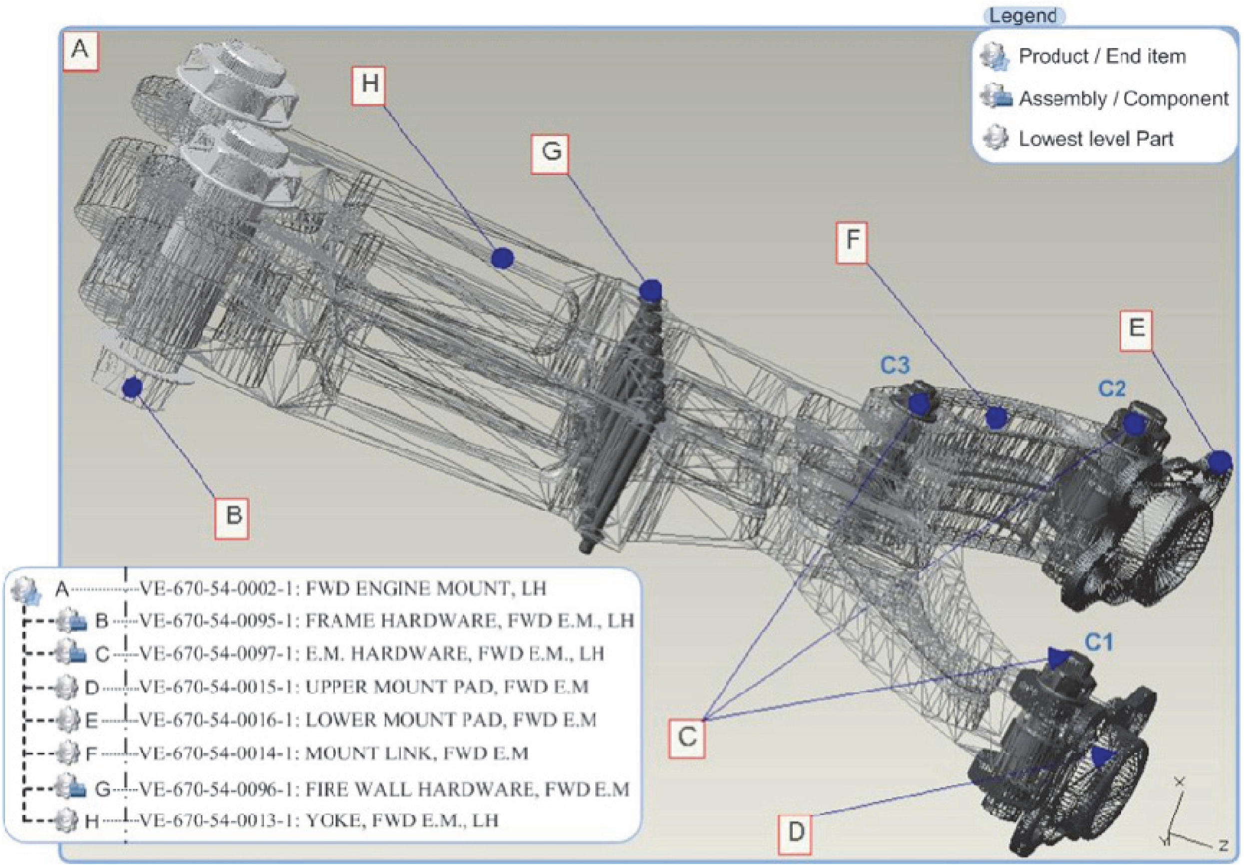


Figure 4.15: A design arrangement of the forward engine mount components

At a point defined by the project milestones and the design maturity, the processes of design and process planning concretely begin to overlap, while a great part of the manufacturing activities will start after the full access is provided to the product definition data. These data are clustered within the CDMU (as previously defined). They can then be filtered and manipulated by following the effectivity rules within the agreed upon configuration management context. Hence, while starting with the same functional arrangements as the designers, both the manufacturing and development & testing engineers have to use their expertise to deploy strategies to build, assemble and test the artefact based on the shop floor resources and constraints. Regarding the forward engine mount, its manufacturing has been found to necessitate a quite different structure from the as-designed one. This manufacturing structure follows a strict chronology of operations to end-up with the physically functioning artefact. More precisely, two sets of operations (the pressing of the bearings and the fastening being the principal in both) have to be executed to obtain:

- Manufacturing assembly MFG-ASSY-003 which includes the upper mount pad, the yoke and the hardware C1.
- Manufacturing assembly MFG-ASSY-002 including the lower mount pad, the mount link and the hardware C2.
- Manufacturing assembly MFG-ASSY- 001 which includes both MFG-ASSY-002 and MFG-ASSY-003 connected via the C3 connector; the bearing being pressed into the yoke as a prior operation.

In a final operation, all the other components are installed, completing the physical assembly of the mount. Instrumentation components are furthermore collected in a new assembly (INST-ASSY) with no correspondence on the design side. Figure 4.16 schematically exhibits the resulting product structures.

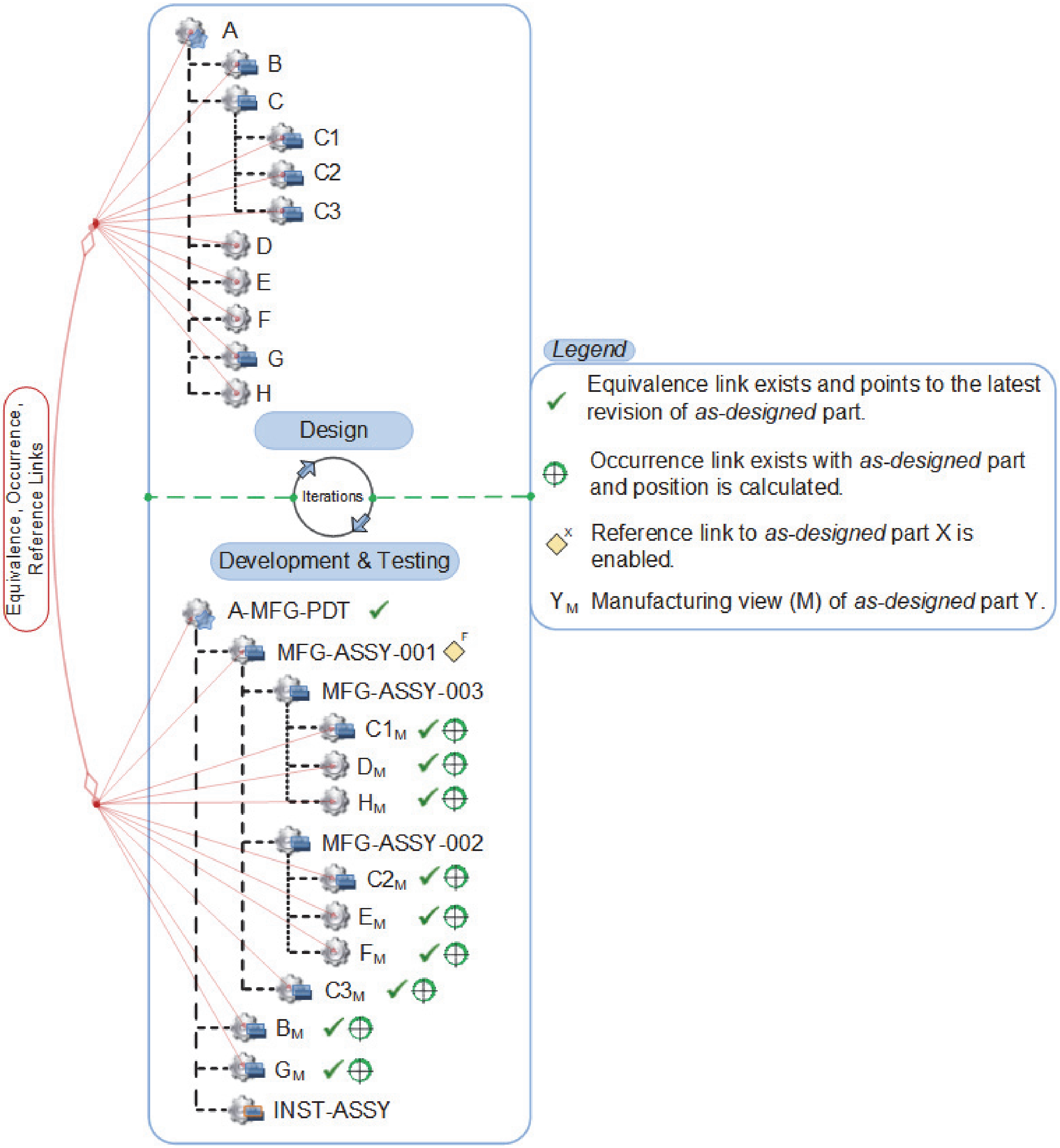


Figure 4.16: Development & Testing complementary structure of the forward engine mount (schema)

The scenario has been implemented in the pilot simulation environment as shown in Fig. 4.17 (in this case Windchill PLM tool from Parametric Technologies Corp.). In the exhibit from the PLM tool simulation, the top level development & testing product (A-MFG-PDT) corresponds to VE-670-54-0002-1_PT while MFG_ASSY_001, MFG_ASSY_002, MFG_ASSY_003 and INST_ASSY correspond to 0000009261, 0000009262, 0000009263 and FWD_E_M_ATTACH.

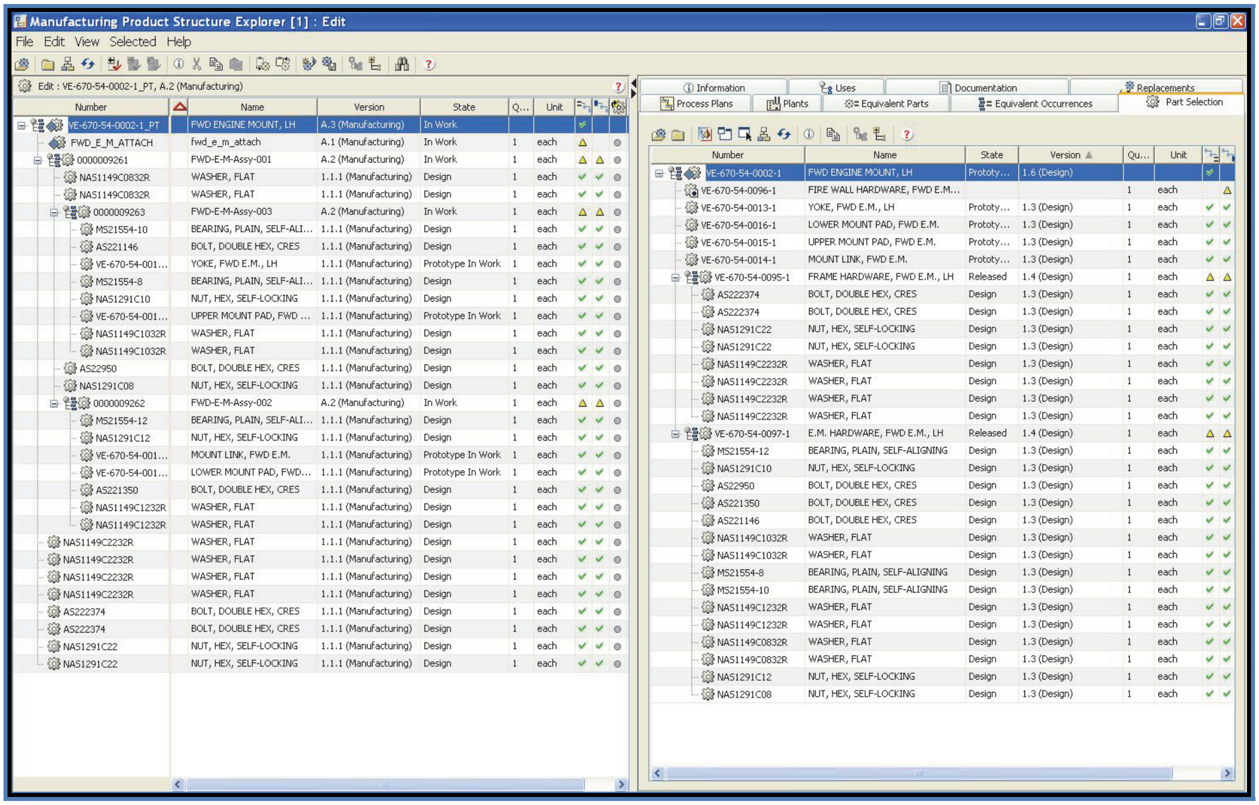


Figure 4.17: Development & Testing complementary structure of the forward engine mount (simulation). Courtesy of Parametric Technologies Corp.

The complementary Development & Testing structure and its links to the Design structure are maintained throughout the design, manufacturing, and testing iterations, as previously described in Fig. 4.13. Without these links, managed through the simulated MPM system, maintaining coherency between the product structures would normally rely on hand-offs, then manual operations carried out with decoupled Excel files or other independent applications, which increase scatter, the risk to errors and quality issues. Furthermore, the described links are not static but dynamic and are updated as the design evolves, which is necessary to keep stakeholders on track (see green, grey and yellow icons on the right side of each product structure in Fig. 4.17). This coherency is ensured via the previously described *non-isomorphic* hierarchies model as well as the links between the complementary structures.

As a concrete illustration of potential iterations, the mount link F (Figs. 4.14 and 4.15) is a connecting part that is susceptible to undergo changes on the yoke (H) side interface during development activities. Any change to the link may directly affect the manufacturing assembly MFG-ASSY-001 and then trigger minor or major changes to the related process plan; this includes changes to the standard bearing and fasteners composing hardware C3. Activating the reference link between the mount link F of the as-designed product structure and the manufacturing assembly MFG-ASSY-001 allows the stakeholders to track and propagate the design changes to the as-tested product structure. By supporting this process within a single PLM system, it is possible to avoid errors and quality issues that could arise through the use of separate or decoupled systems.

The planned test procedure, detailed within the test plan, therefore points to a unique as-tested structure. Concerning interaction with manufacturing execution, the serial or lot numbers of manufactured and supplied parts are identified to track the physical parts. Performance data and run times are accumulated both at the build and the detail itinerant hardware component level to comply with design substantiation requirements and inform the current and future design decision-making. In addition, a part deviation severity code is provided by inspectors for each part used in the test to inform team of the conformity and condition of the part. This is done because some parts are used in more than one test and more generally because the level of approximation to be taken into account for the test cannot really be estimated without considering variation introduced with prototyping and testing. To close the loop of this learning by experimentation process, test results along with the initial test plan are included in a test report for further analysis and design refinement. This data can also be associated to the relevant components of the as-tested product structure. As these components are explicitly linked to the as-designed product structure, the use of complementary product structures can facilitate the communication of the results with members of the design and manufacturing teams.

The approach discussed so far ensures that the required physical tests and procedures and derived as-tested structures and outputs are connected to the as-designed structure. Furthermore, the hardware testing transactions and prototype information tracking have been emulated in a commercially available PLM platform as an initial simulation to converge towards the targeted framework.

4.3.2.3 Industrial Experience

As introduced in chapter 3, the participatory action research reported in this thesis was part of the PLM transformation of a lean manufacturer of complex aerospace systems. This transformation was later supported by a third-party consulting firm for its execution, which culminated into the large-scale deployment of a new PLM platform across all divisions of the company. Regarding the development and testing phase and, as exposed herein, the inexistence of prototyping and testing functionality in commercially available PLM platforms has led the PLM design team to customize the selected platform within the constraints of the tool limitations and the project design decisions. A preliminary assessment using VSM showed that an improved design-manufacturing-test collaboration framework can reduce hand-offs by 85%, eliminate all redo's in the interaction and also accelerate the overall plan-build-test-feedback process by approximately 40%. Along with reduced hand-offs, scatter and waste during product development, high level benefits from this customization included:

- Improved collaboration between Simulation/Development/Test and Design/Product Definition by leveraging the same reference data constructs to accelerate simulations, experimental builds, testing and feedback processes;
- Better managed costs by reducing the interaction between multiple application tools. This to standardize and centralize the dBOM capability;
- Improved traceability to the requirements through the connectivity between as-required, as-designed and as-tested structures for a lean approach to the regulatory requirements;
- Increased productivity by reuse of development engineering assets using standardized business objects which helps to reduce complexity.

Some components of the framework discussed here were leveraged in the customization, especially the as-tested complementary structure which manifests into the dBOM and uBOM. Based on the scope of the project phase (four phases PLM program) mBOM and CDMU integration were deferred to subsequent phases, which led the team to select the alternative option of representing dBOM in eBOM structuring (see Fig. 4.11) and rather build a robust integration with the manufacturing execution system (MES) through the uBOM. While this demonstrated, through successful user acceptance test (UAT) gates, to be a valid and valuable approach in meeting the requirements, the necessity to manage two BOMs was pointed out as a drawback in live operations. Indeed, legacy applications by layering directly on top of the relational database management system (RDBMS) manipulated both parts and hardware builds reference IDs in an automated fashion, making the association invisible to the user. This is difficult to achieve in modern object-oriented PLM platforms where the user interacts directly with the object which is the digital representation of a company artefact or an existing physical item. As the part object definition cannot be equated to physical builds (one part can manifest into many builds) the different sets of information need to remain separate to some extent but at the same time, integration and automation is required between the two as they refer to the same definition from a certain viewpoint. This is currently the subject of PLM design enhancements with the vendor for a next generation dBOM. Figure 4.18 below displays dBOM and uBOM (as-built) in the context of the industrial large-scale deployment.

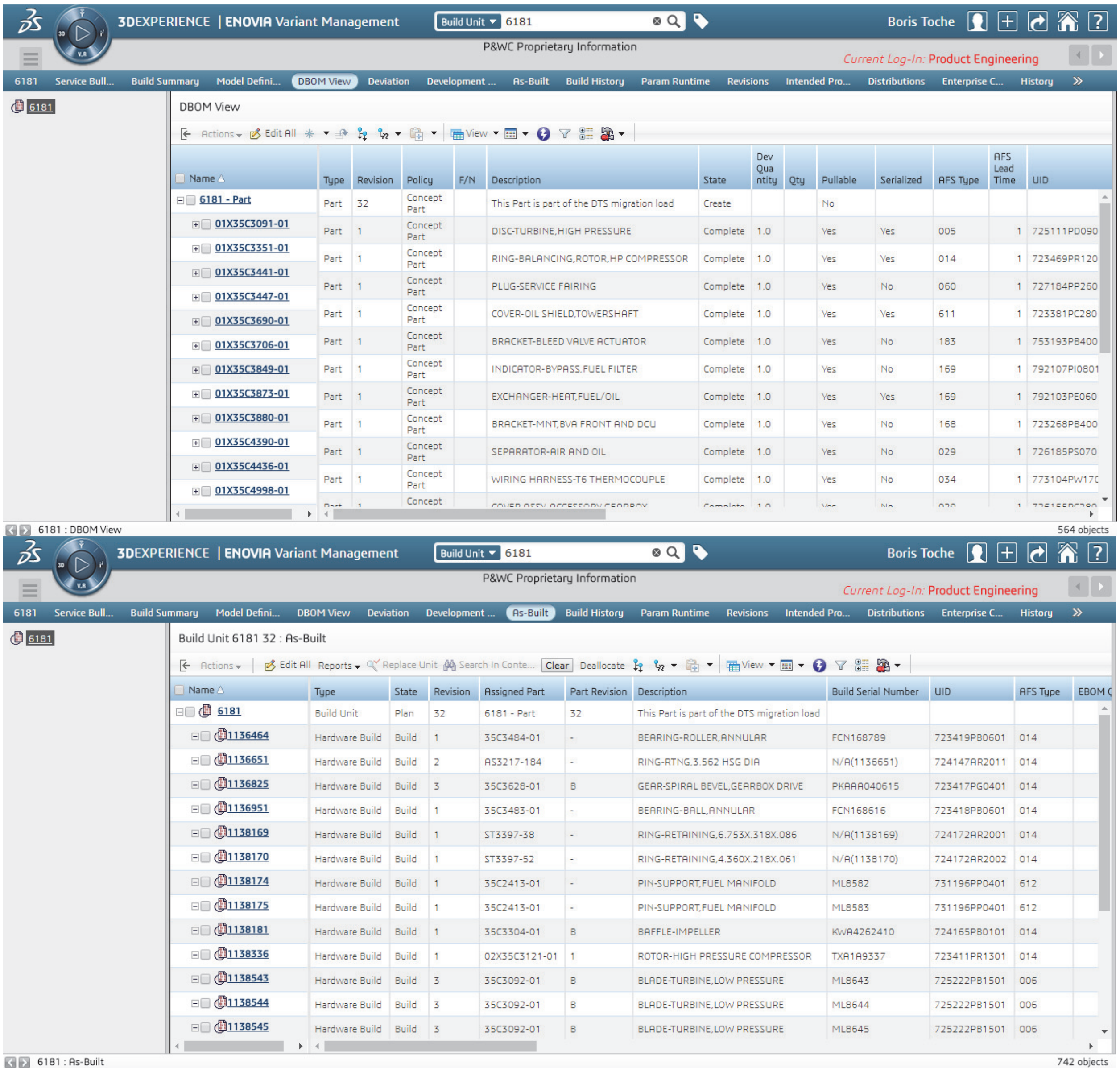


Figure 4.18: An industrial large-scale deployment of *as-tested* structure. Courtesy of Dassault Systemes, **3D**EXPERIENCE 2014x

The absence of configurable virtual product or CDMU in this industrial PLM deployment has also demonstrated to be critical for effective product structuring, Configuration Management (CM), flexibility and Concurrent Engineering (CE). This is evidenced by the related productivity and potential configuration bandwidth losses, which are not presented in this dissertation for confidentiality reasons. The experience however leads to positive conclusions about grounds for believing that there is a relationship between the configurable virtual product and flexibility, time, costs, CM, CE performance and furthermore SBCE during product development programs, thereby disproving null hypothesis $\mathbf{H1_0}$.

4.4 Conclusion

The role of product, manufacturing, as well as test and prototyping data and the specificity of information in PLM have been presented to illustrate the context in which products are now developed in the extended enterprise; some challenges in this context are again highlighted below:

- There is an increasing demand for flexibility and integration between multiple internal and external participants in the PDP;
- Systems and information structures are often silo-arranged and incompatible;
- Single version of the truth, collaboration, traceability and reusable assets are of major concern;
- Products and processes are becoming more complex, and;
- Supporting tools are getting more harmonized than specialized in order to reduce scatter, waste and ultimately streamline the processes and enforce security, intellectual property and export control rules.

Figure 4.19 represents a tag cloud generated from the PLM transformation structured focus group data collection form, which includes the overall content as discussed and documented during the campaign.

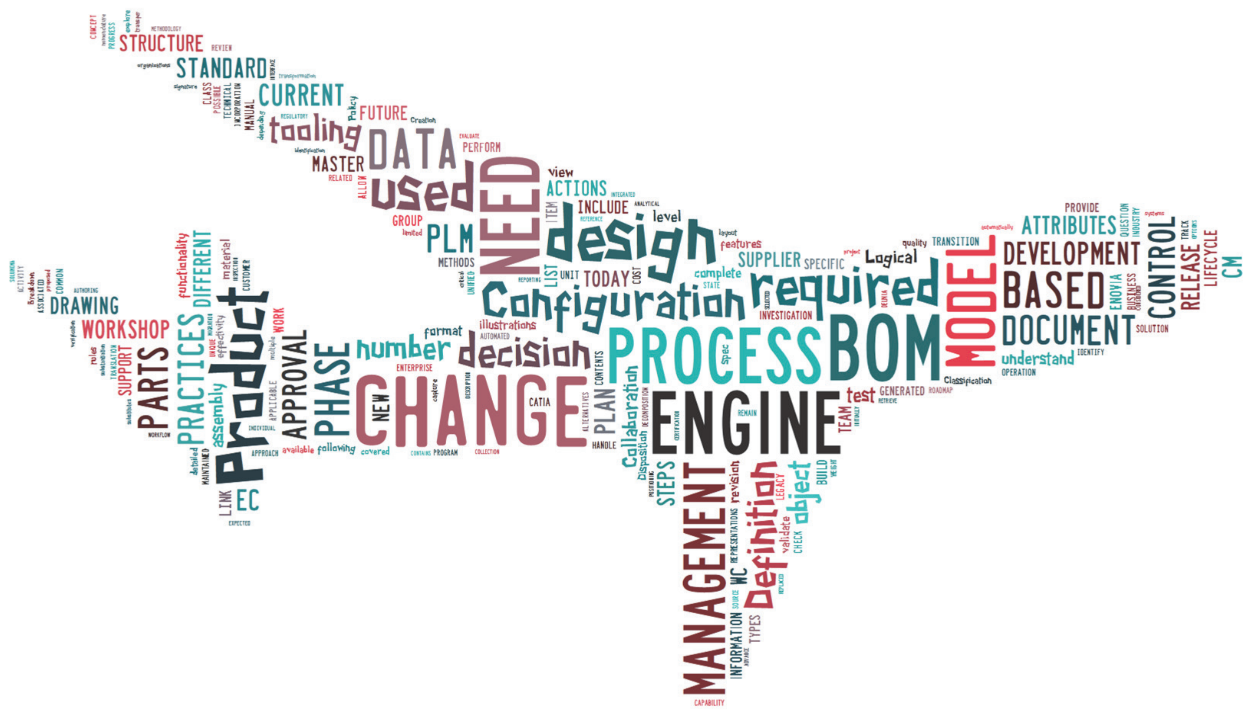


Figure 4.19: Tag cloud from the PLM transformation structured focus group data collection

The role and place of the testing and refinement phase during the PDP have been discussed and key aspects concerning prototyping and testing activities were presented to demonstrate the interoperability needed between design and testing teams involved in the process of the product realisation. The study also showed that there is still an important place for physical prototyping in the product realisation cycle even if virtual prototyping has significantly evolved over the last decade. It is also possible to find a proper transfer point between virtual and physical prototyping to optimize both approaches.

The methodology and tools required for proper configuration management for virtual and physical prototyping and testing have been clearly described. It was shown how the proposed framework, based upon the development of explicit links between as-designed and as-tested complementary product structures, supports collaboration between design and test engineers, as well as the management of the relationship between physical instantiations and virtual prototypes. Through a concrete case study, the proposed use of complementary information structures and processes, representing various disciplines views within the product development cycle, has been shown to enable the coordination of the evolving as-design and as-tested product structures design-build-test iterations. The potential to efficiently support design and testing collaboration at a large scale has also been presented and discussed on a real life experience basis. This experience in industry demonstrated the value of the proposal and at the same time, highlighted the difficult path to the desired state. Core components of the proposed framework have shown through experience to be necessary and sufficient to achieve the benefits, these are:

- The configurable product structuring approach to enable required flexibility between design, simulation and testing through the development iterations and explorations;
- The *non-isomorphic* hierarchies and complementary information structures, extended to *as-tested* structure, to enable required interoperability and traceability between design and testing.
- The link-based interconnectivity between the structures to strengthen synchronisation between the views, allow for contextual 3D visualisations and to support effective change propagation in heterogeneous domains.

The proposed configuration management approach enables the parallel exploration of multiple prototypes by synchronising design, development, simulation, manufacturing and testing streams while securing all gathered knowledge. This promotes institutional learning capabilities through structured set-based prototyping. The framework therefore underpins a valuable potential for supporting practical implementations of set-based concurrent engineering (SBCE) which is the keystone of lean product and process development (LPPD). The next chapter will develop on the proposal by extending it to a newly devised multi-domain Configurable Complementary Structure (CCS) model that can support cross-functional virtual and physical prototyping towards SBCE. This model will be extrapolated to the Learning Value Streams (LVS) model in support to practical implementations of LPPD.

CHAPTER 5 CONSTRUCTION OF THE LEARNING VALUE STREAMS (LVS) MODEL

A multi-domain product modelling that entails variability and configurability is devised in this chapter to support explorations of a product platform design space by allowing various disciplines involved in the product lifecycle to consider sets of distinct alternatives concurrently so as to appropriately inform a set-based design convergence process. The novel Configurable Complementary Structures (CCS) model draws upon appropriate design process models identified in SBCE systematic literature review (chapter 2), then findings from chapter 4 Descriptive Study I, to develop and extend essential components of a product lifecycle framework that can support collaboration towards SBCE. This CCS model is subsequently extrapolated to the Learning Value Streams (LVS) model by refining and combining all studied LPD essential enablers into a cohesive whole that can holistically support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective.

This chapter, in the strict sense, constitutes Prescriptive Study of DRM as applied. The first part of the chapter summarizes influences towards CCS as converged from the systematic literature review and Descriptive Study I. The second part discusses the theory of domains as well as this thesis novel multi-domain product modelling conceptual framework. In the third part, parallels are drawn between models of the design process and each separate domain described previously in order to step by step build a product modelling approach that is suitable for set-based design practical implementations in product lifecycle management contexts. The multi-domain product modelling conceptual framework, then language is combined with elements of variability and configurability in the next part to devise the novel CCS model. The last part consist of the extrapolation to the LVS model which is followed by conclusions in relation to the research questions and hypotheses.

5.1 Prelude

Hypothesis, explorations, validations and findings from the previous chapter have led to postulate the basic components of a product lifecycle framework that can support collaborative prototyping and testing towards SBCE. This framework is based on a *non-isomorphic* hierarchies model for product structuring which encompasses the notions below:

- Multi-view links to synchronize complementary structures (*as-planned*, *as-tested*) with evolving *as-designed* alternatives;
- Instantiation to trace assembled and tested physical prototypes. Instantiation consists in materializing a part or component by identifying and tracking the physical object with a digital one. This is done by assigning the unique supplier or shop-floor serial/lot number to the digital object which is then called *serialized instance*;
- Effectivity rules to handle multiple options in parallel in order to represent design alternatives, corresponding manufacturing alternatives as well as potential physical yields. Figure 5.1 shows an example of product architectural options effectivity used to manage configurations (alternatives) from a baseline modular architecture. This configurable product structure combined with instantiation generates frozen as-tested BOMs representing physically assembled and tested prototypes.

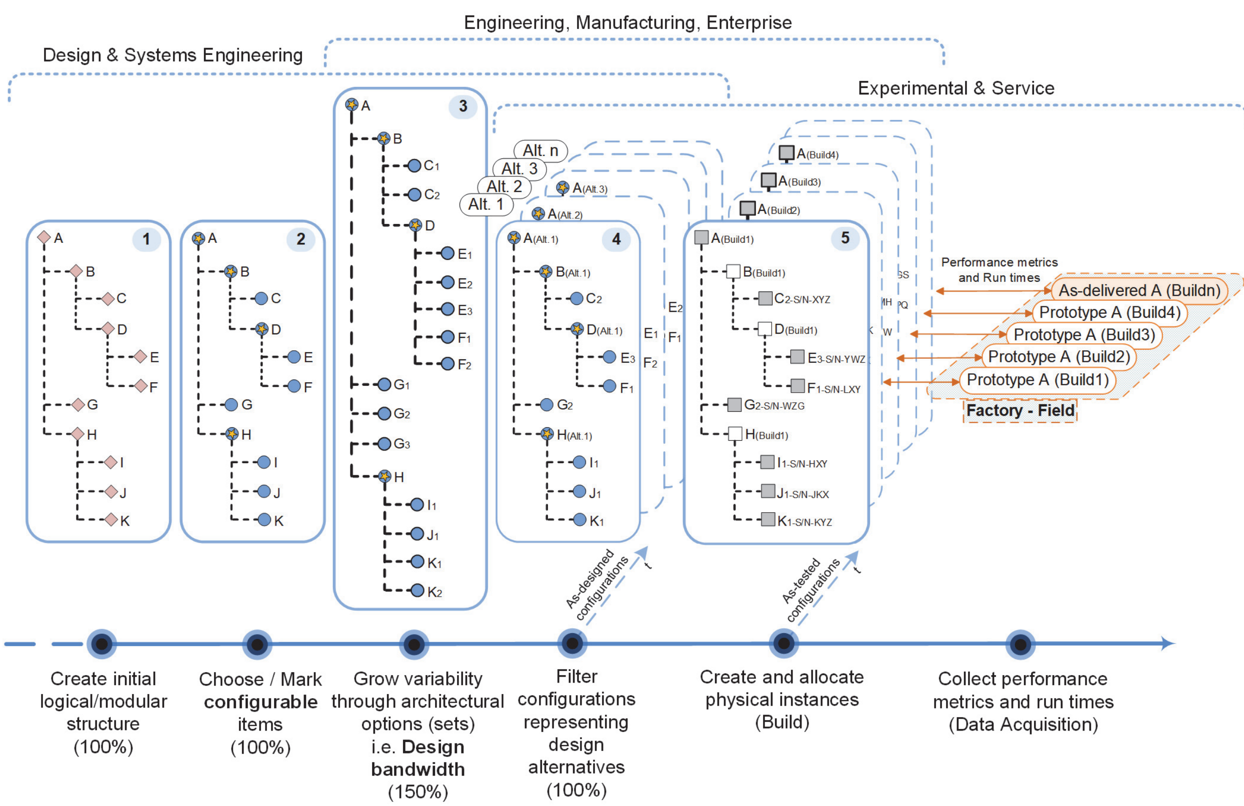


Figure 5.1: Simplified configuration methodology to represent sets and physical prototypes (manufacturing process not represented)

Figure 5.1 configuration methodology for non-isomorphic hierarchies and complementary information structures is synthesized from Descriptive Study I by emphasizing SBCE underlying capabilities. The methodology was demonstrated in chapter 4 to enable the parallel exploration of multiple prototypes by synchronising design, development, simulation, manufacturing and testing streams while securing all gathered knowledge. This was found to promote institutional learning capabilities through structured set-based prototyping, to allow for contextual 3D visualisations including as-built DMU and to support effective change propagation in heterogeneous domains.

From Fig. 5.1 steps sequence, it should be noted that sets are introduced following a baseline modular structure because capabilities in platform design and variability (modularity and scalability[4]) are acknowledged to intrinsically facilitate SBCE (Johannesson et al., 2017; Levandowski et al., 2014b; Schafer & Sorensen, 2010). Indeed, variability within a product architecture makes it practicable to switch between design alternatives.

The baseline architecture displayed in the first block of the diagram stems from the functional breakdown of the end item referred to as the logical structure, which belongs to the technological domain. The remaining blocks as well as the overall approach discussed in chapter 4 are rather elements of the physical domain, which is extended in this thesis to introduce a new *existential* domain reflecting builds and traceable instances of a product. This chapter will further develop on multi-domain product modelling approaches for large-scale industrial applications of SBCE and, then, step by step perform the construction of the proposed Configurable Complementary Structures (CCS) model. CCS will finally be extrapolated to a holistic model that can support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective.

[4] Modularity is the variability introduced by interchangeability between design solutions in a product architecture whereas scalability is the variability of design parameters for the physical implementation of a design solution (Johannesson et al., 2017).

5.2 Multi domain views in engineering design

The development of a new product or product platform starts with the definition of requirements, which usually manifest into specifications described in terms of functional requirements (required functions of the product), constraints (conditions for the solution) and evaluation criteria (to validate the solution with regards to the problem statement) (Colton & Pun, 1994; Pahl & Beitz, 2013; Suh, 2001; Ullman, 2009). These specifications form the basis for the cross-disciplinary development as they are interpreted by each discipline within their own domain of expertise in order to build representations that correspond to the intended product and its realisation process. While textual languages and sketches at the start of design can be seen as informal ways to describe the product (Huet et al., 2009), product models and the corresponding modelling languages provide more formal means to structure the product/process design information on different abstraction levels, different levels of detail and from different perspectives (Erens, 1996). As such, domain partitioning is common in engineering design literature in order to represent various aspects of a technical system while designing. This partitioning works in conjunction with product models with the purpose of describing both abstractions of functional requirements and abstractions of the resulting design (Andreasen, 1991; Erens, 1996; Hubka & Eder, 2012b; Pahl & Beitz, 2013; Suh, 1990). To elaborate, Hubka and Eder (2012b) in their theory of technical systems (TTS) presented five levels of abstraction of a technical system which correspond to domains that may be used to represent various aspects of the technical system in terms of: purpose; process structure; function structure; organ structure; and; component structure. In axiomatic design, the conceptual, product and process design phases are realised by iteratively mapping from the customer domain to the functional domain, then to the physical domain and finally the process and logistics domains (Suh, 1990). Andreasen (1991) in his theory of domains (ToD) proposes a partitioning based on Hubka and Eder's TTS and which consists of the process domain, function domain, organ domain and component domain. It is important to note that domains are meant to either support models of the design process (design theory) e.g. domains in axiomatic design (Suh, 1990), or product models e.g. domains in the *chromosome* model (Andreasen, 1992). Similarly, the representational formalism adopted in each case may differ as models of the design process focus on design synthesis, whereas product models mainly support the logical definition of the product and its realisation process. While a common reference to the functional domain seems established, there is a difference in the meaning given to the term “process”. Process in axiomatic design for example refers to the manufacturing process whereas process in other partitioning refers to the transformational processing of the technical system from which functions are derived. There is also a difference in the terminology used by the authors when it comes to the technological and physical domains. The technological domain, as it will be defined below, corresponds to the organ structure in the TTS and ToD, while the physical domain corresponds to the component structure for the two and remains the same in axiomatic design. However, as mentioned above, product models would typically reflect parts (physical embodiment) in the physical domain, when design process models, for example in axiomatic design, would reflect design parameter choices which are perceived as physical decisions but not necessarily embodiment definitions. This thesis focuses on product models that can support practical implementations of SBCE in product lifecycle management contexts. To that end, three domains below can be synthesised from the literature:

- Functional domain, to describe the required functions independently of any particular solution principle. These functional requirements or requirement specifications are frequently described at the design problem abstraction level by using verbs (motion, transformation, control, etc.), nouns (material, energy, information, etc.) and design parameter values (area, volume, weight, force, torque, angle, speed, etc.). Functional requirements can be laid out hierarchically by linking and decomposing them into sub-functions (Hubka & Eder, 2012b; Pahl & Beitz, 2013), which will then result in a functional breakdown of the product. However, functional dependencies and interfaces, e.g. material, energy, signal flows, are often of non-hierarchical type. Function variants can be introduced to support the variability in customer requirements (customer options) while also defining the commercial compatibility and combination rules between the functions (Claesson, 2006; Erens, 1996);
- Technological domain in which functions are implemented in technologies i.e. design solutions represented by operating system modules. This domain is used to define the product architecture, and logical decomposition (logical structure) required to support the architectural definition of the product during early design phases and onward. The technological domain is tightly integrated with the functional and physical domains in

order to enable an architectural definition of the product that satisfies the functional requirements on one side (regardless of the physical implementation) and, on the other side, to provide the means by which product instances can be embodied in the physical domain by complying to the functional requirements. As this logical structure (design solutions) is meant to represent the conceptual definition (architecture, functional systems, location and logical links) without physical part embodiment (Jiao, Simpson, & Siddique, 2007), the product model in the technological domain usually allows for variability (modularity, options), interchangeability, flexibility and reusability in Advance Engineering, Design and Systems Engineering. This functional-based modularity provides the opportunity to the participants to model and assess platform designs without solidifying physical architecture intentions. Scalability is furthermore enabled based on the variability available while instantiating a product in the physical domain. A granular element of the logical structure can be regarded as a functional feature or logical feature i.e. design solution, which represents a system component in the logical structure based on its function and location within the product platform. The logical feature therefore acts as a link between a functional requirement and physical embodiments (parts) which satisfy that requirement. In some industries like aerospace, the logical feature can be identified using standard nomenclature for function and location within the vehicle or equipment (e.g. ATA standard, S1000D) with the purpose on enhancing the use of the functional decomposition as required in Aftermarket, Service and Maintenance areas;

- Physical domain reflects the physical embodiment of the technologies and solutions described in the technological domain. The product is usually modelled in this domain using different representations than the technological by focusing on shapes, fit, the way by which technological solutions can manifest in real life and the means by which construction of the product can happen. Geometry, DMU, engineering and manufacturing structures elaborated in chapter 4 represent outcomes of the product modelling language within the physical domain. As a product instantiated in the physical domain may evolve through engineering changes, the product model in this domain is required to support change propagation across multiple views and also allow for mechanisms to secure and retrieve past and future configurations (see Configuration Management in chapter 4).

It is believed that the initial specifications may not be limited to one single domain as they are simply the essence of the required functions, technological and physical constraints (Erens, 1996). For this reason, specifications are embedded across a product model constructs as the last represent the backbone for structuring product information in each involved domain. This information is represented with the corresponding product modelling language which may be shared across domains or not. Except for considerations for after-sales support (Männistö, 2000; Männistö et al., 2001; Maurino, 1993; Watts, 2012), and the digital twin concept to some extent (Glaessgen & Stargel, 2012; Tao et al., 2017), the capture/representation of physical prototypes or in-service serialized artefacts is rarely addressed within the design and product structuring literature. The physical domain discussed in the literature consistently refers to the embodiment of a design artefact (engineering definition), which, as discussed in chapter 4, does not belong to the realm of the resulting tangible and serialized instances (Experimental/Operations/Service). Männistö et al. (2001) recognize such realities by stating that "data structures suitable for manufacturing are not the most appropriate for after-sales. After-sales requires its own concepts and its information must be presented in a view of its own". Multiple serialized instances of the same system (as-designed i.e. physical domain) may exist in the field or during test rig experimentations with the corresponding life performances and potential failures recorded at the serialized component and build configuration level. This is of a special importance in the case of companies providing products as service or "uptime" plans (Männistö et al., 2001). The type of view (serial instantiation, allocation, build configuration and performance tracking) and the array of information required to be structured in the context of this domain is different from the physical domain as it is referred to in the existing literature. Drawing upon explorations, findings and recommendations from chapter 4, it is proposed in this thesis to extend the functional, technological and physical domains to include a new *existential* domain reflecting builds and traceable instances of a technical system. Figure 5.2 below illustrates the adopted multi-domain framework. The product model in each domain area is the mainstay for structuring the domain specific information which in this case relies on *non-isomorphic* hierarchies models (Van Den Hamer & Lepoeter, 1996) for product structuring on one hand and, on the other hand, modelling languages for non-compositional systems. According to Erens (1996), there is no modelling language for non-compositional systems that is able to predict the behaviour of the system within the context of the theoretical framework. It might be possible to understand the behaviour for some aspects of the system but it will usually remain difficult to simulate the overall system behaviour from the constituent part behaviours. In contrast, compositional systems are represented by product models that are based on theories from natural science and mathematical/physical/chemical principles governing the behaviour of the system components. The behaviour of the product can therefore be predicted in the context of the theory as the relationship between the system components is also understood. This is rarely achievable in the case of complex systems that involve various interacting technologies and cross-influential laws like mechatronic systems (Buur & Andreasen, 1989; Erens, 1996). Also, even though for some routinized engineering fields, physical/chemical laws and mathematical principles might be able to reflect the behaviour and function of particular modules or components, they do not readily support the system-level development process itself. Modelling languages for non-compositional systems, in contrast, present this capability. In the remainder of this thesis, triangles in diagrams will denote functions (Design/Systems Engineering), lozenges or diamonds will denote technology modules (Design/Systems Engineering), and circles will denote physical assemblies and components (Engineering/Manufacturing/Experimental) while squares will represent serialized instances of a physical item (Experimental/Operations/Service). Dashed lines crossing domains represent the relationships between the domain structural views. In below simplified example, requirement satisfaction relationship, functional coupling and other cross-domain relationships are displayed for one specific item. These relationships will be further discussed in section 5.3.

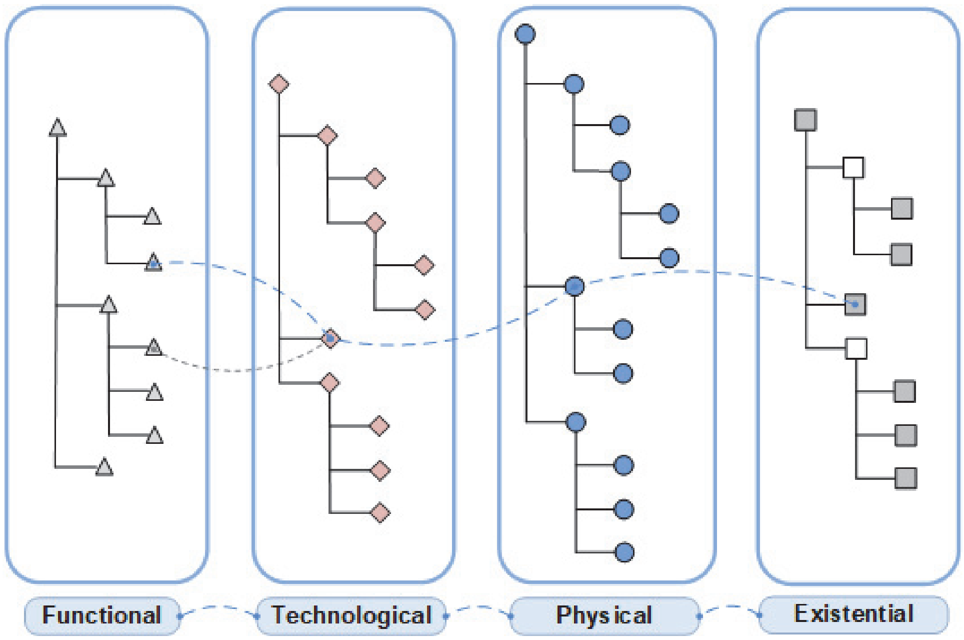


Figure 5.2: Adopted multi-domain product modelling framework (no variability represented)

As discussed in chapter 4, the challenge in using *non-isomorphic* hierarchies models for product structuring lies in enabling and maintaining the interconnectivity, communication and consistency between the different models or structural views, especially in a concurrent engineering environment (Anderl, Malle, & Schmidt, 1992; Brière-Côté, Rivest, & Desrochers, 2010; Brissaud & Tichkiewitch, 2001; Claesson, 2006; Erens, 1996; Van Den Hamer & Lepoeter, 1996). This problem does not exist in the level-by-level model (single model) but it is concurred with Erens (1996) in this thesis that "the application of more than one technology in a product family design is the main reason for not rendering the functional model, the technology model and the physical model into a single model". The construction of robust relationships/links between the models or views is believed to be an effective mean to overcome the challenges that arise with multiple product models/views (Brière-Côté et al., 2010; Erens & Verhulst, 1997; Fortin & Huet, 2007; Männistö et al., 2001; Maurino, 1993; Svensson & Malmqvist, 2001; Van Den Hamer & Lepoeter, 1996). This has been demonstrated for example in chapter 4 for the required interaction between engineering (as-designed), manufacturing (as-planned) and experimental (as-tested) structural views (all in the physical domain) by using the complementary information structure approach. This approach will be extended in the next section to bridge between the functional, technological, physical and existential domain. Figure 5.3 below exemplifies the adopted multi-domain framework in the case of the development of a turbojet. The focus is on few requirement specifications and system components. The manufacturing process view is not represented and variability is not illustrated.

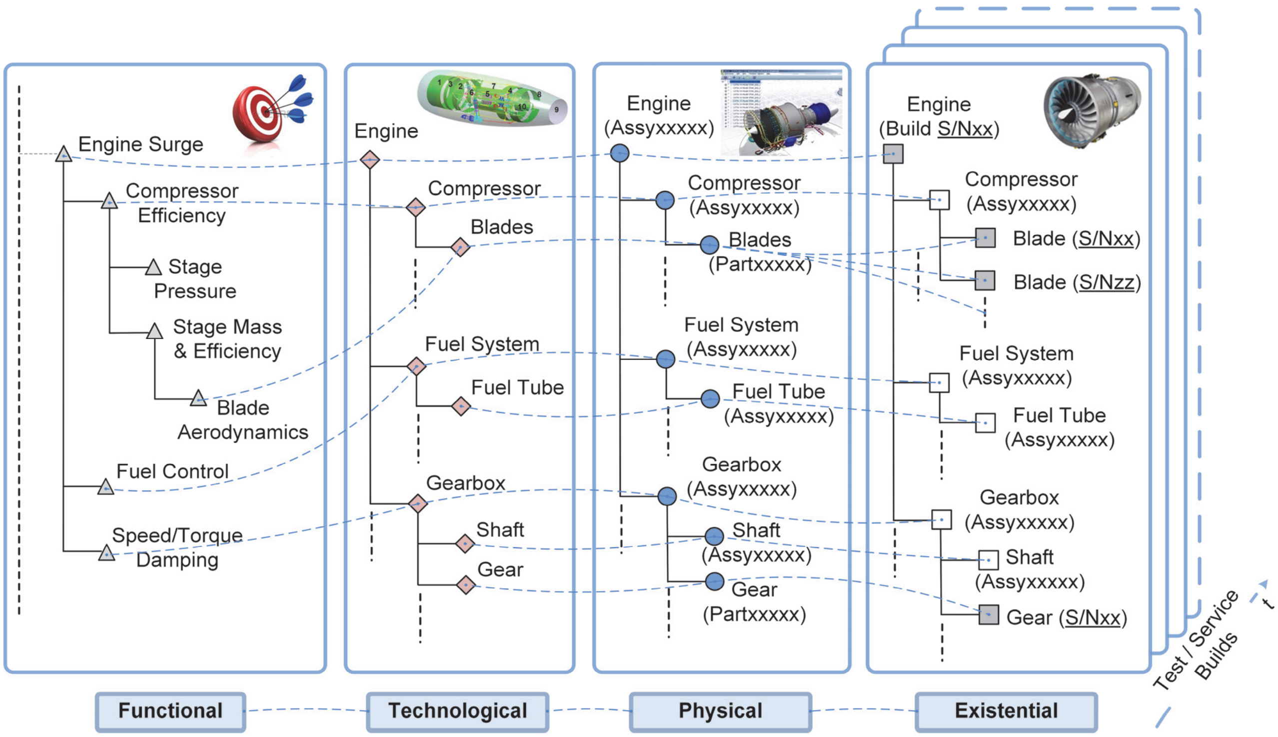


Figure 5.3: Example of multi-domain representations for the development, testing and service of a turbojet (no process view, no variability represented)

5.3 Product models for SBCE industrial implementation

An appropriate design process model than can support practical implementations of SBCE, particularly at the conceptual design stage, was identified during the evidence-based systematic literature review of SBCE in section 2.2.3.5. This Enhanced Function-Means (E-FM) modelling presents the advantage of spanning the functional (FRs) and technological/physical domains (*means* i.e. DSs) while providing a bridge to product modelling through the Configurable Component (CC) framework. Johannesson et al. (2017) basically leverage the combinatorial effects of variability and configurability within the E-FM and CC framework to advocate the strong compatibility with SBCE design space exploration. These authors use variability within the E-FM tree model to handle multiple architectural options that can then be analysed with the purpose of reducing functional couplings (*is_influenced_by* and *interacts_with* relationships) and furthermore, progressively eliminating unfeasible designs at the conceptual level (Levandowski, 2014; Michaelis et al., 2013; Raudberget, 2015). This is also seen as extendable to manufacturing processes (Johannesson & Claesson, 2005; Levandowski et al., 2014a). The framework allows for SBCE convergence processes because it supports: (1) exploration of a product platform design space as well as elimination of unfeasible designs and; (2) preservation of conceptual solution sets until variants are instantiated though the CC framework for embodiment design and reality check. Although the framework evidently shows capabilities at the conceptual level, it remains unclear how the various domain (see fig 5.2) functional groups i.e. requirements engineering, advance engineering, systems engineering, design engineering, components engineering, etc. may interact using it for a leaner and lifecycle approach to product development. SBCE front loading process is also unclear and the multi-domain, multi-disciplinary connectivity that enables value to flow in a structured cross-functional Knowledge-Based environment is not addressed. An attempt is made to fill these gaps by proposing an approach whereby product variants are instantiated from the CC modeller and then passed to a PLM software to engage downstream activities in the development process (Johannesson et al., 2017; Levandowski et al., 2013). Virtual prototyping, simulations and physical tests are subsequently assumed performed through the normal PLM process, then knowledge is produced to inform the E-FM/CC platform design by means of analog feedback, which then helps the product platform design convergence process. This approach discloses dislocated methodologies and tools that promote scatter, hand-offs and waste during product development. For these reasons, it is proposed to transpose the E-FM tree model of the design process into the product model representational formalism found in the literature (see previous section) with the purpose of devising a product model that is compatible with industrial product lifecycle management contexts (see Chapter 4, Descriptive Study I) and lean PD principles (see Chapter 2). This is done in order to converge towards a model that is suitable for practical SBCE implementations using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework, for instance, PDM/PLM. Figure 5.4 illustrates the domains within the E-FM tree model of the design process with the corresponding constructs separated.

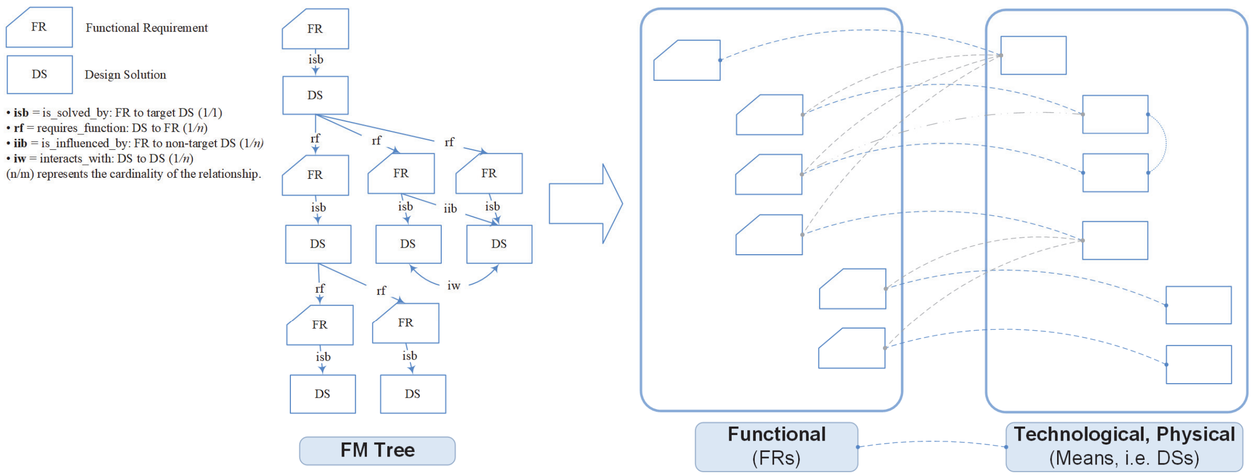


Figure 5.4: Domain view of the E-FM tree model (no variability represented)

Uncoupling the domains constructs within the E-FM tree model appears to result in isomorphic functional and technological/physical hierarchies but this is simply the reflection of the sole functional decomposition hierarchy (design path) underlying the tree. Indeed, isomorphism driven by the design process and actual functional decomposition path, is also present in axiomatic design domains views. This should not be confused with isomorphism vs. non-isomorphism previously addressed between product modelling structural views. That being said, one may still expect the result within the functional domain to correspond to a typical requirement specification breakdown structure usually found in industry (Maurino, 1993; Svensson & Malmqvist, 2001; Watts, 2012). Again, that is not the case as one should not attempt to figure FRs as if they were reflecting a mere requirement breakdown structure (Raudberget, 2015) p.32. Unlike Pahl and Beitz's functional decomposition in which a *function* is further divided into *sub-functions* and so on (Pahl & Beitz, 2013) p.32, E-FM modelling requires the mean (design solution) to be identified before the next functional requirement can be derived, therefore zigzagging between the domains while iteratively building mutual dependencies and potential couplings between functions and design solutions (Malmqvist, 1997). This is the manifestation of Hubka and Eder's *co-evolution* process which is graphically embedded into the E-FM tree (Claesson, 2006). While such co-evolution is quite similar to the zigzagging pattern found in axiomatic design (Hillström, 1994), it can be contrasted with other approaches found in industry and engineering design literature e.g. Pahl and Beitz, p.31, where functional decomposition may be performed independently from any particular solution, even though co-evolution must somehow happen mentally in order to decompose further. A mapping is usually done afterwards by moving from the functional decomposition onto the technological or physical domain, therefore implying transformational matrices or simply, relationships/links between the domains constructs. This is simply governed by the design process in place and not necessarily a strict theory of designing. The objective here is not to advocate a specific design synthesis model but rather to derive product modelling approaches that can support various processes, especially set-based design (multiple alternatives synthesis/exploration), in a lean and product lifecycle management perspective. Besides, a ripple effect of the simultaneous and reciprocal FRs/DSs definition is the fact that DSs, as entailing both technological and physical domains, can neither be readily figured as if they were reflecting a logical structure as described in section 5.1. Such hierarchy can only be expected from the CC tree (technological domain) which is used to instantiate product variants in their actual physical architecture (Claesson, 2006; Johannesson & Claesson, 2005). All above leads to the observation that the E-FM tree model is better appreciated with design matrices similar to axiomatic design rather than in hierarchical tree with the purpose of reflecting product architecture readily usable in a product lifecycle management context. All things being equal, the idea here is to foster *non-isomorphic* hierarchies product models across the distinct domains/views as this is argued to be the common case scenario during practical implementations of multi domain interactions in industrial product lifecycle management contexts. Resulting domain structural views are usually different as studied for example in chapter 4 for the required interaction between engineering, manufacturing and experimental complementary information structures. The emphasis in this study is therefore on making parallels between the E-FM tree model of the design process and each separate domain described in section 5.1 in order to build a product modelling approach that is suitable for SBCE practical implementations in product lifecycle management contexts. Similar approach was demonstrated by Malmqvist (1997) to be relevant and effective during, for example, the transposition of the E-FM tree model into the representational formalism of the *chromosome* model and domains (Andreasen, 1991, 1992) in order to capture design history information. Figure 5.5 below illustrates the adopted multi-domain product modelling. The constructs within each domain are not meant to be strict equivalents of FRs or DRs or CCs but rather transpositions into the domain typical constructs as described from the corresponding literature in section 5.1.

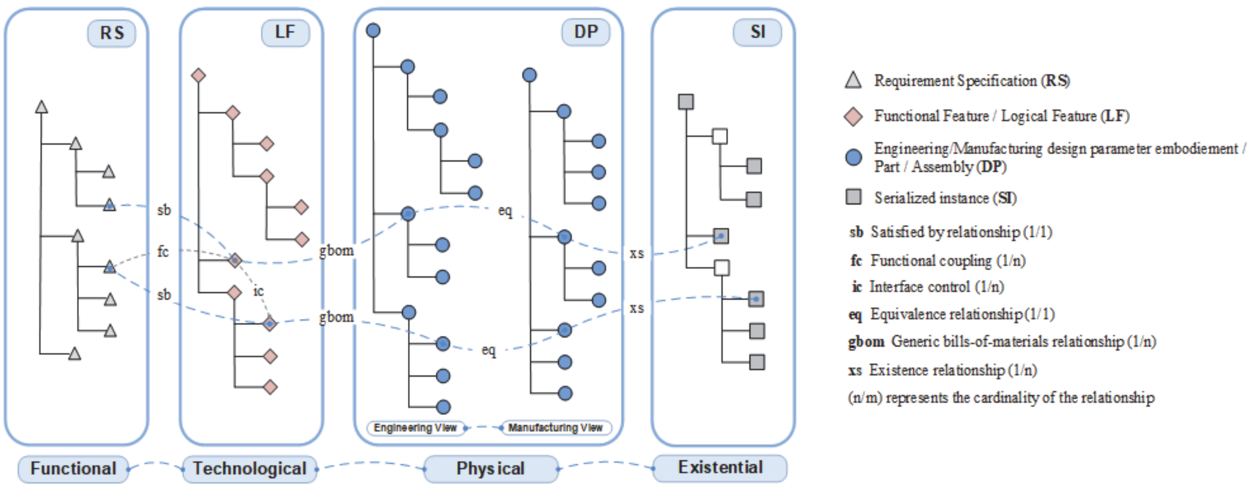
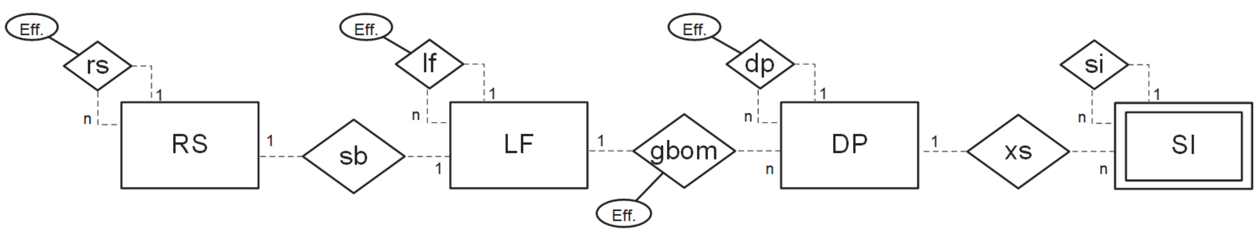


Figure 5.5: Adopted multi-domain product modelling (no variability represented)

Assuming the technical system "process" and functions can be merged into one functional or *transformational* domain (Andreasen, 1998), the product modelling as constructed is aligned with the theory of domains representational formalism found in (Andreasen, 1992; Andreasen et al., 1996; Erens, 1996; Hegge, 1995; Hubka & Eder, 2012b; Männistö, 2000; Maurino, 1993; Svensson & Malmqvist, 2001; Van Veen, 1991; Watts, 2012) with the addition of an *existential* domain as argued in this thesis. Cardinality 1/1 is given to *satisfied by* (**sb)** relationship i.e. requirement specification (functional requirement) to target design solution, in order to comply with the independence axiom in axiomatic design. Functional couplings that should be investigated for uncoupling or decoupling (Suh, 1990) are modelled using a separate relationship between RSs and design solutions i.e. *functional coupling* (**fc**). This relationship can be seen as a product modelling equivalent of *is_influenced_by* (iib) relationship described in the E-FM tree model of the design process. Although hierarchical dependencies among design solutions are modelled within the technological domain hierarchical structure, it is necessary to capture interactions between the design solutions i.e. *interface control* (**ic**) for the sake of the same independence axiom. This relationship can be seen as a product modelling equivalent of *interact_with* (iw) relationship described in the E-FM tree model of the design process. Equivalence relationship (**eq**) is the link between engineering and manufacturing views of the same physical artefact within the physical domain (see chapter 4 for details) while existence relationship (**xs**) is used to reflect the serialized components as tested or in service. Occurrence relationships (**oc**) for 3D visualization across the domain views and reference relationships (**rf**) for change propagation across heterogeneous domains are not represented to ease readability. These two relationships were elaborated in chapter 4. The **gbom** relationship (*generic bills-of-materials*) is a manifestation of the adoption of the *Generic Product Structuring* (GPS) concept (Erens, 1996; Erens & Verhulst, 1997; Hegge, 1995; Hegge & Wortmann, 1991; Van Veen, 1991; Van Veen & Wortmann, 1992; Wortmann & Erens, 1995) with the purpose of enabling the required variability and configurability while modelling product platforms in the technological domain on one hand and, on the other hand, while instantiating product variants in the physical domain. Drawing upon findings from Erens (1996), it is agreed that the concept spans the functional domain too as it can similarly support modelling variability in customer requirements i.e. translated in engineering terminology. GPS is discussed in more details in the next section.

5.4 The Configurable Complementary Structures (CCS) model

The generic product structuring (GPS) concept basically provides an answer to the issue with describing variability at every single level of a product structure in order to define a recursive and non-redundant product family modelling language across domains (Erens, 1996). GPS leverages the notion of parameter (variable feature) with parameter values (option values) to allow setting an expression condition at any level of a platform single product structure in order to later dynamically retrieve a specific configuration where a selection condition is met. This removes the cumbersomeness of handling every variant product structure separately. Configuration constraints that exclude some combinations of parameter values are also used to ensure only valid selection expressions are passed to generate coherent product variants. To elaborate, the generic bill-of-material (GBOM) concept translates a customer-order commercial specification (set of valid parameter values) into a production-oriented variant bill of materials by retrieving generic preferred modules and then, physical components, that meet the selection condition (Hegge & Wortmann, 1991; Van Veen & Wortmann, 1992). GBOM purpose is specifically about generating variant product structures for customer-driven manufacturing (ATO, MTO, PTO, CTO) by efficiently translating a flexible product variant's commercial description into a coherent variant product structure that is suitable for fast paced realisation processes (Wortmann et al., 1997). While GBOM supports a configuration-oriented modelling of product platforms by underpinning interdependencies between the functional (customer requirement), technological (generic modules) and physical (component) domains, GPS represents the underlying generic product structure modelling by which the domain construct ranges are parameterized at each level of the intended platform product structure tree. This can either be perceived from the physical domain standpoint to drive sales-delivery processes (Brière-Côté et al., 2010; Hegge & Wortmann, 1991; Van Veen & Wortmann, 1992; Wortmann et al., 1997) or strictly from the technological domain in support to product platform conceptual design (Erens, 1996). However, GPS modelling may present some limitations when it comes to engineer-to-order (ETO) product configuration because required alternatives are not necessarily understood and bounded before actual customer orders are received and ETO design is started. A well define modularity, scalability and foreseeable business strategy may help mitigate the issue but it is preferable to have mechanisms in place to adapt to unplanned customer demands while maximising the reuse of existing designs. For these reasons, Brière-Coté, Rivest and Desrochers (2010) propose an adaptive generic product structure (AGPS) approach by which constructs are categorized into common features (invariant), parameterized features (reuse of existing) and special features which are meant for specific ETO product needs as drawn from Mesihovic and Malmqvist (2004). This approach allows to aggregate new variability into a product platform single product structure while maximising the integration with the existing parameterized framework. In a nutshell, AGPS appends discovered variability (special features) to the generic product structure through ETO development cycles, which means new parameter or parameter values, modules and components are incrementally added to the structure to form the new integrated variability asset that enables reusability for the next cycle. Besides the ability to handle special features that support the current ETO design, the remaining part of AGPS is a GPS incremental update which is driven by a well-defined family configuration update process across ETO development cycles. GPS and AGPS therefore display valuable capabilities for modelling variability and configurability for ETO product platforms in multiple domains and development stages while fostering design reusability. According to the objective herein, it is proposed to use similar product configuration modelling approach by adopting a representational formalism that is suitable for product lifecycle management implementations. Such formalism is for example used by Peltonen et al. (1998) who explain that an ordinary structure extended with optional, alternative and parametric items can be regarded as the *explicit structure* of a configuration model. These authors state that the explicit structure together with the constraints governing the configuration retrieval process “roughly correspond to the idea of a *generic product structure*”. In product lifecycle management contexts, explicit structures are formalized using the notion of *effectivity* with most prevalent usage in engineering change configuration management (Watts, 2012). Effectivity, which is defined on the relationship between two constructs (within or across domains), is basically a parametric expression associated to the child construct that determines the conditions for which the construct is “in or out” in the context of its parent or another upper level construct. The parent construct in turn is deemed *configurable* as it contains children that can be filtered “in or out” based on their individual effectivity parametric expressions. Variability and configurability are therefore maintained at the *configurable* construct level which usually appears unresolved i.e. 150%. This explicit structure requires a valid effectivity expression to resolve/filter coherent configurations (100%) that bear meaning in the specific domain context. Figure 5.6 shows a conceptual entity relationship diagram (ERD) of the proposed CCS model using Chen (Chen, 1976) notation style. Functional coupling relationships are not represented to ease readability.



sb: Satisfied by relationship

gbom: Generic bills-of-materials relationship

xs: Existence relationship

rs: Requirement specification/Functional requirement tree structure relationship

lf: Logical feature/Functional feature tree structure relationship i.e Logical structure

dp: Design parameter tree structure relationship e.g. DMU, as-designed (eBOM), as-planned (mBOM)

si: Serialized instance tree structure relationship e.g. as-built, as-tested, as-maintained

Eff.: Effectivity expression attribute. Expression format is [C;P;R] i.e. [Context;Parameter;Range]. e.g. [Platfrom X; Thrust Reverser ;*Yes, No*]

Figure 5.6: CCS conceptual entity relationship diagram

It can be seen from the ERD that the relationship between the constructs in the same domain is simply homonym of the construct and it allows for explicit structures in the domain except for existential domain which do not allow to set effectivity on the relationship at this point. This is justified by the fact that a serialized individual is inherently resolved. Also, SI is modelled as a weak entity because it requires a DP to exist, for instance a Part definition. Within the technological domain, architectural modularity is defined by the various effectivity paths at each level of the logical structure tree (LFs), whereas scalability is reflected by the range of design embodiments (DPs) that can be selected through **gbom** effectivities to instantiate coherent product variants. Similar variability can also be maintained directly in the physical domain as explained in chapter 4. This is graphically synthesised in Fig. 5.1 where the first block is used as a template of the intended modular product architecture (100%) whereas the explicit structure is actually maintained in the physical domain. Such approach is suitable for companies with DMU/BOM-centric development processes whereby formalising a separate flexible logical abstraction of the product platform is not seen as mandatory. Although the advantage of architectural explorations without physical embodiment is inherently removed in this case, and also tracking from the physical embodiment back to the functional requirement may be difficult, the approach is sometimes justified by a requirement to reduce the burden of maintaining an additional structure with no real operational value (perception is only DMU/BOM does). Indeed, productivity and lead time concerns may arise in the case of fast-paced development processes where there are very less changes to the logical constitution of the product and participants can quickly interact using/re-using product structures in the physical domain i.e. DMU, eBOM, mBOM rather than trying to formalise a tribally known logical architecture beforehand. In these situations, even for breakthrough designs, advance design cross-sections, layouts or master lines that result from preliminary multi-disciplinary design optimisations (Panchenko et al., 2002) appear sufficient to kick-off the DMU/BOM centric development process for a selected alternative. In these cases, physical domain scalability represents the sole variability that is further leveraged and there is no apparent need to maintain a formal explicit logical structure that contains alternative designs and the rationale for eliminating them. This is to say, it is not always given that companies are willing to maintain product structures in the technological domain. This may necessitate ability of the product to be modularized, a product portfolio that requires SBCE as discussed with Table 4.1, a strong business strategy, resource allocation and understanding of the value in maintaining logical structures and alternative design data on the long run. Figure 5.7 below illustrates the approach from a product platform conceptual design standpoint whereby logical abstraction and multi-domain variability are fully leveraged i.e modularity and scalability. The catalogue of parameters, parameter values and constraints that drives the effectivity expressions in the tree is showed on the top right as inspired by Erens (1996) p.135. Constraints for example do not allow to filter configurations such as [x1,-,z2,-] or [-,y1,z1,-] because they do not resolve into coherent product configurations (PC) or so-called, valid architectural options (AO). In the context of SBCE, such catalogue and resulting explicit structure can be understood as the design space or design bandwidth to progressively narrow by allowing other functional groups to view/filter product alternatives in their own domain. Functional groups can therefore develop their own options in reference to the explicit structure and by using a common PD framework, shared constructs and data sets (single version of the truth). Each alternative option is then evaluated through virtual simulations, prototyping and test. Data as gathered for each combination of options is associated to the corresponding configuration, thereby becoming codified knowledge available to the whole community in support to set-based convergence for current and future development programs.

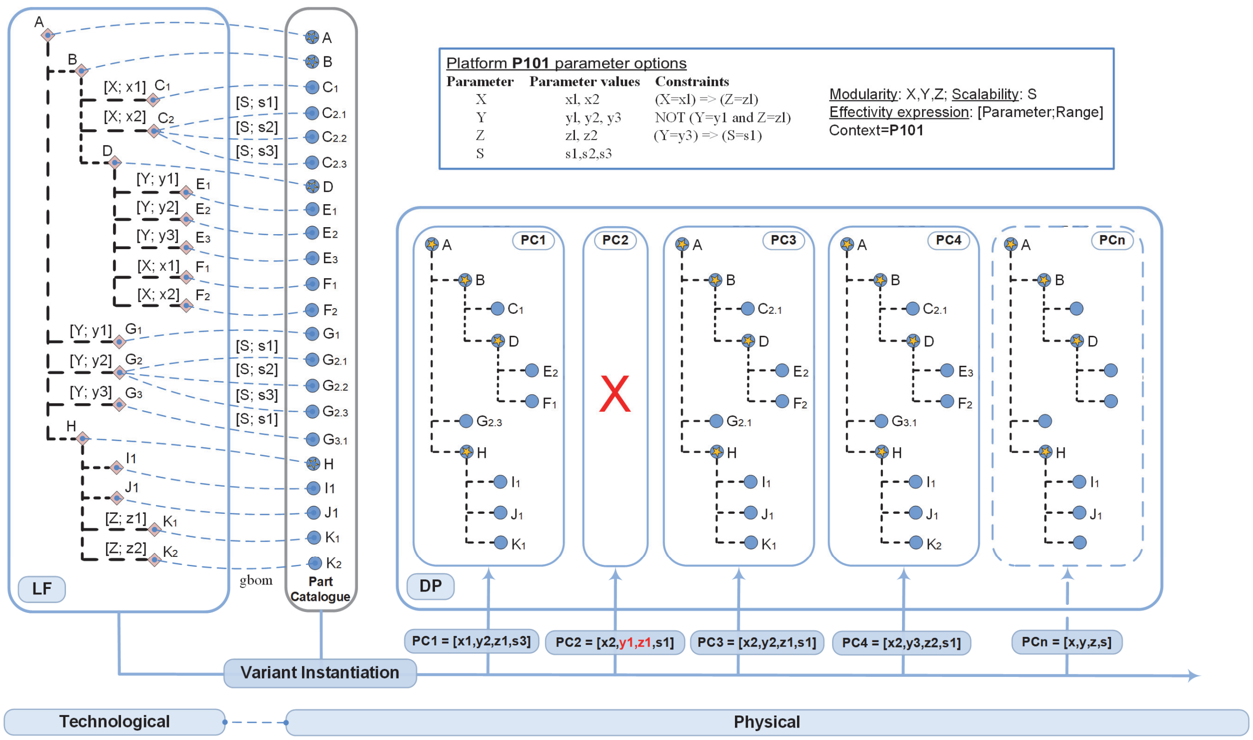


Figure 5.7: Illustration of CCS cross-domain implementation (Technological to Physical. No manufacturing process represented)

The adopted effectivity approach allows for product configuration modelling in the functional, technological or physical domains and is furthermore compatible with configuration engines (configurators) typically available in PDM and PLM systems, see (Mesihovic & Malmqvist, 2004). These configurators can be designed to resolve architectural option effectivities (parameter, parameter values) and constraints when applied to technological or physical constructs (Sabin & Weigel, 1998; Soininen, Tiihonen, Männistö, & Sulonen, 1998). Also, configurators have already proven very effective and robust for resolving change evolution effectivities (date, unit, product versions, etc.) during product development and beyond, see examples in (Mukherjee, Ryan, & Wason, 1994; Orr, Panuganti, Ryan, Sambataro, & Wason, 1993).

It is claimed that the multi-domain product modelling (section 5.2), variability and configurability approach devised herein together hold the potential to support explorations of a product platform design space by allowing various disciplines involved in the product lifecycle to consider sets of distinct alternatives concurrently so as to appropriately inform a set-based design convergence process. This is in support to the implementation of the first set-based design fundamental principle as stipulated by Gosh and Seering (2014), see principle A in section 2.2.1. It is also claimed that the approach allows for the preservation of conceptual solution sets until variants are instantiated in the physical domain and data is cross-functionally collected to inform the decision-making process. This is in support to the implementation of the remaining set-based design fundamental principle i.e. principle B in section 2.2.1. It is argued that the multi-domain approach can effectively support implementations of these fundamental principles in the sense that, by using the proposed framework and, as noted by Gosh and Seering (2014), the principles can manifest themselves in all phases of the design process, not limited to the conceptual phase or the interface with detailed design phases.

The proposed multi-domain product modelling combined with the variability and configurability components form the multi-domain Configurable Complementary Structure model (CCS) that partially fulfills **RQ2** recalled below:

RQ2: What is an appropriate approach for various domains of expertise within the aerospace industrial product development to exchange on the basis of alternative design solutions and furthermore, narrow down to an optimal design by following a set-based convergence process?

Next section will provide additional details on the set-based convergence process.

5.5 Extrapolation to the Learning Value Stream (LVS) model

With CCS at its core, the Learning Value Stream (LVS) model is devised to encompass the core LPD enablers identified in chapter 2 (fulfilment of **RQ1**) as well as a set-based convergence approach to the lifecycle virtual and physical prototyping interactions studied in chapter 4 (fulfillment of the remaining part of **RQ2**). This is done in order to converge to a holistic model that can support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective (fulfillment of **RQ3**). RQ1 and RQ3 are recalled below:

RQ1: What aspects, characteristics and features of the aerospace industrial product development are catalysts of a potential transition to SBCE and LPD?

RQ3: Does a holistic model exist or can it be developed to support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective?

5.5.1 Set-based convergence

CCS, as elaborated so far, is based on a common multi-domain product modelling framework that allows various disciplines involved in the product lifecycle to consider sets of distinct alternatives concurrently while delaying decisions to first learn by simulations and experimentation i.e. data gathered in structured, interconnected CCS domain views. Although CCS provides a practical implementation framework for SBCE in a lifecycle management perspective, it does not explicitly prescribe design synthesis or SBCE elimination process. Complementary methods should be considered for this purpose. For example, functional couplings (**fc**, **ic**), identified while modelling the product platform in CCS, can be analysed for each architectural option (AO) in a Design Structure Matrix (DSM) (Steward, 1981) in order to assess the weakness of the option from the independence axiom standpoint. The assessment can support elimination of the option as inferior to another. Raudberget (2015) finely describes such set-based narrowing approach by converting AOs E-FM functional couplings (*iib* and *iw* relations) to entries in DSMs in order to compare them and proceed with elimination of the weakest AOs. Besides, basic approaches to set-based elimination include: trade-off studies, curves (Ward & Sobek, 2014); generic decision matrices (Pugh, 1991) applied to elimination processes; Analytic Hierarchy Process (AHP) (Saaty, 1990) applied for example by Maulana et al. (2016); morphological charts (Cross, 1989) applied by Raudberget (2015) in spreadsheet utility form; the set-based selection grid for communicating and eliminating alternatives by Sobek et al. (1999) and; other selection/elimination grids like Quality Function Deployment (QFD) (Hauser & Clausing, 1988) or Choosing By Advantage (CBA) (Suhr, 1999) which is preferred for example by Parrish (2009) in her practical implementations of SBCE in BIM supported civil engineering. These grids and matrices use technical and other qualitative aspects/criteria of a design from different domain perspectives to weight and assess the feasibility and performance of a design alternative as combined from available options. Such proven selection/elimination tools are seen as complementary to CCS when implementing SBCE and there is no prescription on a preferred method as it is agreed with Parrish in this thesis that “literature cannot prescribe a set of steps to implement a set-based design process, since it is context-specific. It varies with the stakeholders involved, the design phase, the decision unit, and the project itself” (Parrish, 2009) p.266.

As part of making decisions to eliminate unfeasible designs, the refinement phase in SBCE usually consists in communicating and overlapping alternative options from the disciplines and functional domains. As discussed during the literature review in chapter 2, even though trade-off curves, morphological charts or selection grids/matrices can support compatibility reviews and decision-making about multiple alternatives, overlapping range options from many different views is generally perceived as complex and difficult to achieve. However, although Digital Mock-ups (DMU) and furthermore Functional DMU (FDMU) and industrial DMU (iDMU) extensively support the conventional industrial PDP (Drieux, 2006; Enge-Rosenblatt et al., 2011; Garbade & Dolezal, 2007; Herlem et al., 2012; Lazzari & Raimondo, 2001; Mas et al., 2014), prototyping (virtual and physical) and testing (including simulations) are rarely addressed as actual means to enable the SBCE overlapping and decision-making process.

It is argued in this thesis that virtual prototyping i.e. DMU, FDMU (Enge-Rosenblatt et al., 2011; Fukuda et al., 2013; Schneider et al., 2010; Stark et al., 2011; Vosgien, 2015), virtual factory simulation e.g. iDMU (Mas et al., 2013a; Mas et al., 2014; Menéndez et al., 2013), digital factory (Salehi & Wang, 2017), and the interconnectivity with physical prototyping as developed in chapter 4 can be leveraged within the CCS model as means for overlapping and analyzing multi-domain independent solution sets. The approach discloses the potential for each discipline to develop their own solution sets virtually by using variability and configurability within the CCS model, then overlapping with others within the virtual space. This CCS 3D-based overlapping can support early assessments of unfeasible/weak design alternatives based upon past prototype information, solution set clashes and incompatibilities identified while simulating superimposed discipline-specific solution sets within the configurable virtual space. Figure 5.8 below shows examples of FEA, rotor burst simulations, manufacturing simulations and early maintainability assessments for an aircraft pylon structural layout alternative (1 of many combinations from available design solution options). Each functional group can deploy its own solution options against the other group options (filtered by effectivity within the CCS model), thereby overlapping sets to perform required assessments and to inform the set-based elimination process.

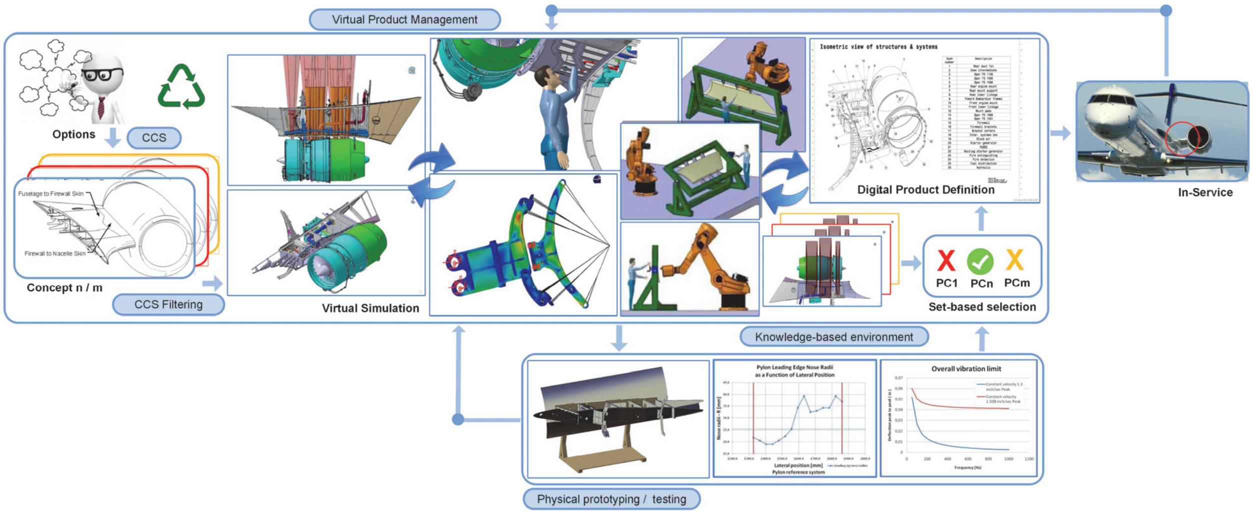


Figure 5.8: Multi-disciplinary virtual assessment of a design alternative

As each design alternative is materialised by a separate configuration from the CCS model, it is possible for all stakeholders to communicate on the basis of a multitude of possible solutions at a given point in time and, therefore, document them accordingly. When required, physical instantiation of a design alternative can be performed, representing a physical prototype that is built, tested and for which all the gathered data is associated with the product-model-instantiated and configuration-tracked structure, see chapter 4 *as-tested*. The data is maintained in a common PD framework against each design configuration and potential prototype instances. It is then used/re-used to inform current and future set-based selection processes/matrices by leveraging the Knowledge-Based environment.

5.5.2 Extrapolation

The CCS model multi-domain configurability extended to include 3D-based overlapping and set-based elimination tools together fulfills **RQ2**. This overall approach is valuable in fostering a product lifecycle oriented and enterprise-level structured Knowledge-Based environment with the purpose of continually implementing and improving a company practice of SBCE. By extending this approach to encompass LPD enablers synthesised in chapter 2 (**RQ1**), it is possible to fulfill **RQ3** by devising a holistic model that can support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective. This Learning Value Streams (LVS) model has CCS as a foundation and it continually leverages prototyping, simulations, testing and PDM/PLM-enabled virtual product management to enable LPD as distilled from the existing literature. The LVS model, displayed below, encompasses practical LPD/SBCE enablers and catalysts in a cohesive whole that can holistically support the transition from the aerospace traditional PD to LPD in a product lifecycle perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework. This model emphasizes streamlined processes and institutional learning capabilities through its multi-domain, multi-disciplinary foundational components. LPD pillars as studied mainly in chapter 2 are embedded in this holistic model and the universal cycle of continuous improvement is also reflected.

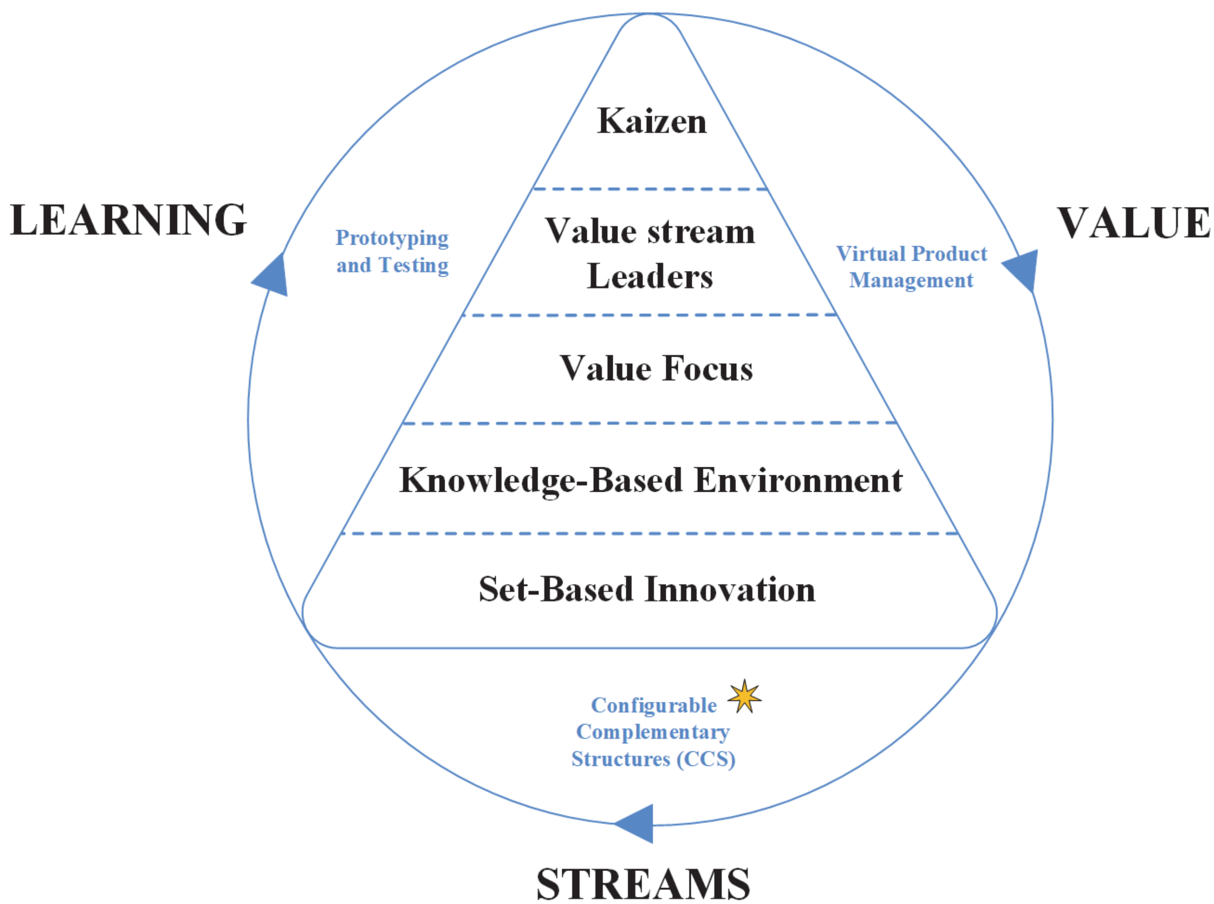


Figure 5.9: The Learning Value Streams (LVS) model

Besides CCS (this chapter), virtual product management, prototyping and testing (Chapter 4), the other components of the LVS model (discussed for the most part in chapter 2) should be recalled or clarified in the context of the proposed methodology.

Set-based innovation (Ward & Sobek, 2014) is simply set-based concurrent engineering geared towards innovation through aggressive exploration of the design space. A competitive company should not be limited to testing to specifications or only designing to meet explicitly known/frozen customer requirements. Ward and Sobek (2014) p.165 state that final design requirements should emerge from "the learning the team does about different design alternatives and their trade-offs" rather than stay "locked in" from early in the process. Based upon Denso's example discussed at the beginning of chapter 4, companies should extensively explore opportunities and consistently generate knowledge to converge to superior designs, regardless of the current demand. By leveraging configurable product structuring such as the CCS model, companies should further their most promising alternatives into product families producible on the same lines. This approach is called *standardized variety* (Ward et al., 1995) and it gives a company both the agility and capability to face current and future market trends. In multiplying alternative prototypes, set-based design practitioners extensively explore the design space in order to assess and enable more variability while creating real options that increase the company's competitive advantage on the long run (Schafer & Sorensen, 2010).

Knowledge-Based environment in the proposed approach refers to the intended PLM-centric environment whereby all stakeholders can interact simultaneously to gather, structure and reuse knowledge about the product throughout its lifecycle. Figure 5.10 below illustrates such environment by highlighting the connectivity between the main lifecycle management threads, their constructs and related typical information ideally hosted in a single PLM environment. The chart was produced after the industrial lean PLM transformation structured focus groups (see chapter 3) and by arranging all collected data using qualitative coding (Strauss & Corbin, 1990). Lifecycle management thread constructs spread within concentric areas in the display while product lifecycle stages unfold radially. The PLM threads represented from the center outward are in order: Configuration Management and Change Management i.e. CM/Change; Model Based Definition and 2D product definition i.e. MBD & 2D; Bill of Material i.e. BOM which is merely Fig. 4.11 transposed in a larger PLM context and; Program Management, Requirement Management and verification & validation i.e. PM/RM/V&V. The product lifecycle is the one used at the company which is usually presented in a sequence of overlapping activities with passport reviews (gate) used to grant full access to the next phase. The phases (gates) are: Product concept (permission to offer); product proposal (permission to launch detail design); product definition; product validation (permission to order production hardware); product delivery (product delivery, lessons learnt and entry into service support) and finally; product maintenance. These phases are cyclically represented in the inner wheel of the chart with the corresponding generic PLM phases aligned to ease understanding. Passport gates are represented by the radii with each description provided on the outmost circumference. This chart is intended for illustration of PLM as a Knowledge-Based environment for product development by including product realisation and product maintenance related information as well. Many of the acronyms in the concentric areas may bear less or no meaning for the reader but that is not where attention should be driven. It should be possible for the reader to reflect on their own experience when it comes to each generic lifecycle stage and lifecycle management thread i.e. each region of the polar grid. Also, this chart do not attempt to prescribe any point-based or set-based development process. Lifecycle stages described are simply examples of the main phases an individual product may go through during its life, independently from other alternatives being considered or a product family design at hand.

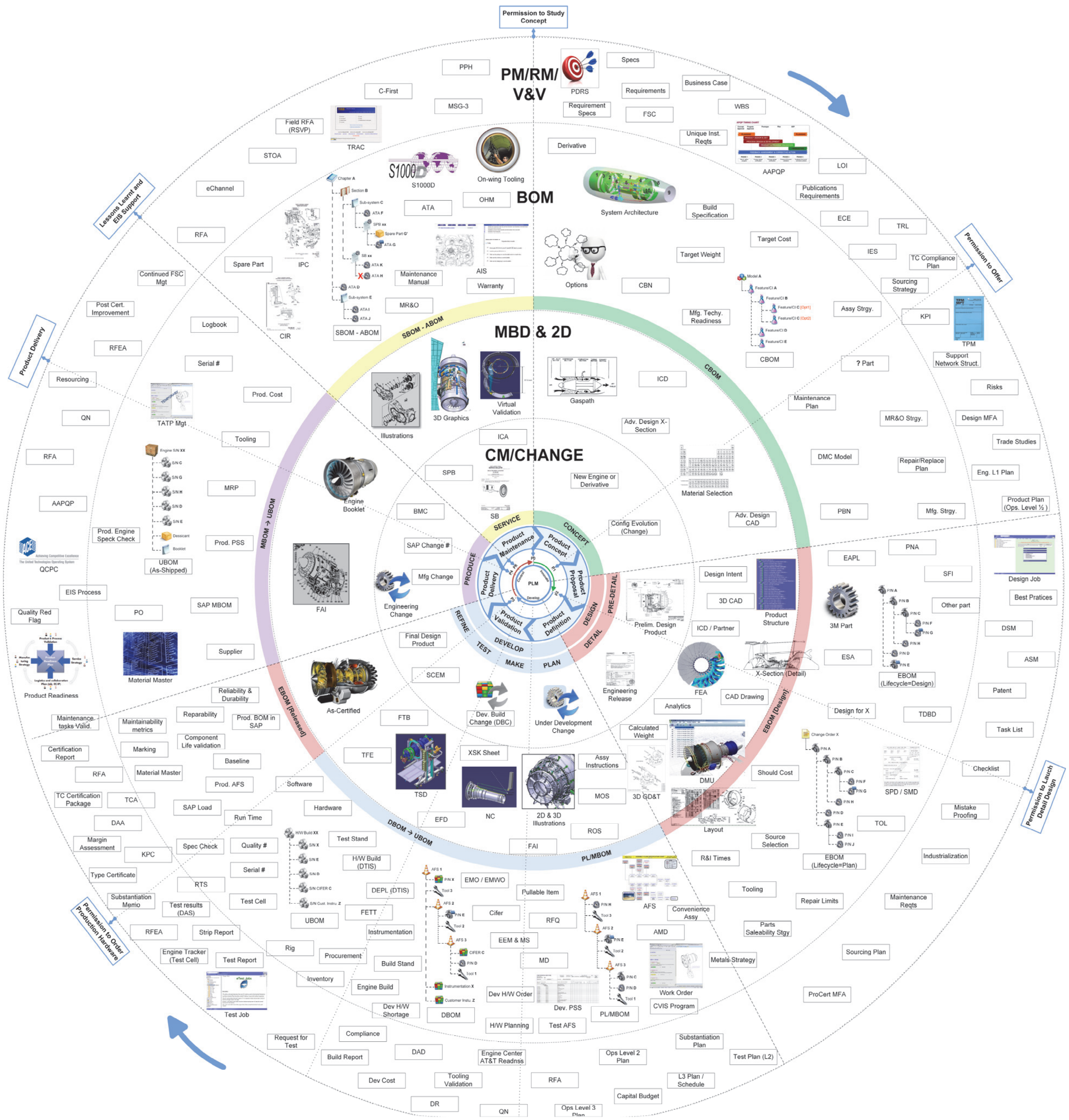


Figure 5.10: PLM Knowledge-Based environment

Value focus in LVS refers to value and flow as discussed in section 2.1.2. According to Ward and Sobek (2014), the aim of a development activity is to produce operational value streams that run from suppliers through factories, into product features and out to customers. These streams do not exist until development processes create them. CAD geometry, FEA, layouts, product structures, Bills of Material, drawings, assembly plans, test results, manufacturing instructions, etc. have value in the sense that they create operational value streams for the main customer that is Production, and by consequence, the end customer who is entitled to benefit from an impressive product quality. Lean Product Development (LPD) was defined as "*the cross-functional design practices (techniques and tools) that are governed by the philosophical underpinnings of lean thinking – value, value stream, flow, pull, and perfection – and can be used (but are not limited) to maximize value and eliminate waste in PD*" (León & Farris, 2011). As far as waste, knowledge, value, and flow are concerned, it was observed during the literature review that the focus should be upon creating value rather than merely eliminating waste in LPD (Browning, 2000, 2003). It was furthermore observed that lean methods in engineering should prioritize streamlining and accelerating flow rather than eliminating waste per se (Browning, 2000; Hines et al., 2006; Oppenheim, 2004; Reinertsen, 2007). This is to say, optimized and faster flow improves interactions in design processes, reducing uncertainty, risk, and ultimately waste. It is commonly agreed that the value of PD can be expressed as a function of information produced on time to minimize wasted efforts and to reduce uncertainty (Beauregard et al., 2014). The right information, in the right amount, available at the right time. In the same vein, Ward and Sobek (2014) argue that lean development focuses on creating *(re)usable knowledge* that contribute to consistently profitable value streams through learning. This is at the root of the learning value streams cycling in the LVS continuous improvement model. The approach to lean focuses on improving multi-domain cross-collaboration by reducing scatter, hanf-offs through streamlined lifecycle management processes i.e. improved flow. More specifically, the proposed model support generating and securing structured knowledge that entails operational value in large-scale industrial contexts, this by fostering institutional learning capabilities through set-based design explorations of product platforms.

A value stream leader (VSL) is responsible for value flow and delivery. VSLs are frequently advocated in lean product development literature by also interchangeably using the terms value stream manager, chief engineer, strong project manager or entrepreneur system designer (ESD). Notable examples of ESDs include Kiichiro Toyoda, Henry Ford, Steve Jobs, Elon Musk or Clarence "Kelly" Johnson. Skunk Works, for instance, is an appropriate example of the typical context that may sometimes be required for ESDs to perform. They usually lead a small dedicated team that controls the development process, from the refinement of a business case, creation of viable concepts, provision of technical design expertise, value stream design and integration, up to the coordination with production engineering and sales (Ward & Sobek, 2014). Indeed, VSLs or ESDs hold both the technical knowledge and responsibility for delivering customer value, making the development project profitable and for driving learning value streams towards creation of (re)usable knowledge. Although many companies not necessarily engaged in PD lean transformations do have experienced people in place with chief engineer or program manager titles, these people often play the role of project managers (Liker & Morgan, 2006) by emphasizing risks management, resources loading and removal of roadblocks to meet the next PD gate. VSLs (or ESDs, chief engineers as referred to in lean) in contrast, enhance cross-functional integration by designing the logical architecture for the product as well as the learning value stream system on one side and, on the other side, by guiding consensus and trade-offs (Ward & Sobek, 2014). From a high level, they provide the vision and technical leadership. VSLs therefore focus on system design, integration and delivery of value by leaving supervision responsibility, functional expertise and scheduling to functional managers. This is known to create a positive natural tension in the resulting matrix organisation, which becomes a source of innovation, as VSLs continually want to explore new territories according to customers' needs while the functional units try to keep VSLs within the envelope of the organisation's technological capabilities (Morgan & Liker, 2006; Ward & Sobek, 2014). This tension is the fuel of the learning value streams cycle in LVS which is circulated by a commitment to institutional learning for competitive superiority. The resulting continuous improvement for the sake of perfection should culminate into a Kaizen system as targeted at the top of the pyramid in LVS.

5.6 Conclusion

Drawing upon SBCE systematic literature review (chapter 2), then a comprehensive study of the conventional PD digital product information context, product structuring for collaborative engineering and prototyping/testing in a lifecycle management perspective (chapter 4), it was possible to postulate the basic components of a product lifecycle framework that can support collaboration towards SBCE. A multi-domain product modelling that entails variability and configurability was devised in this chapter 5 to support explorations of a product platform design space by allowing various disciplines involved in the product lifecycle to consider sets of distinct alternatives concurrently so as to appropriately inform a set-based design convergence process. The so-called Configurable Complementary Structures (CCS) model with its multi-domain configurability extended to include 3D-based overlapping and set-based elimination tools altogether substantiates **H1**$_1$ and **H2**$_1$ which are recalled below:

H1$_1$*: A product structuring model that supports concurrent engineering on one hand and, the configurable virtual product synchronized with prototyping as-tested structures on the other hand, can provide effective means to enable an enterprise level SBCE that spans the product lifecycle.*

H2$_1$*: Virtual prototyping tuned by physical prototyping and, combined with a set-based selection process/matrix, can form an appropriate basis for overlapping and narrowing independent solution sets.*

This CCS model and extended methods were subsequently extrapolated to the Learning Value Streams (LVS) model by encompassing the core LPD enablers identified in chapter 2 as well as virtual product management practices studied in chapter 4 and beyond. This LVS model substantiates **H3**$_1$ which is recalled below:

H3$_1$*: The transition from the aerospace traditional PD to LPD in a product lifecycle perspective and, by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework, can be achieved through the implementation of a holistic model.*

The next chapter will perform a simulation validation of the proposed CCS model (validation of **H1**$_1$ and **H2**$_1$) in the context of a commercially available and widespread PLM platform.

CHAPTER 6 PRODUCT STRUCTURING PILOT SIMULATION

A validation of the proposed Configurable Complementary Structures (CCS) approach is reported in this chapter. This simulation was performed by a small team of experienced engineers and novice designers who leveraged typical off the shelf constructs and configurator of a conventional PLM system in use at the company. Such setting replicates the realistic design context prescribed by DRM for Descriptive Study II. The team composed of the author, one system engineer, one development and test engineer, one product definition integrator, three designers (summer interns) and one CAD/DMU specialist participated in the simulation for four months. This was done as part of a special pilot evaluation for the lean PLM transformation of the configuration methodologies and supporting tools of a lean manufacturer of complex aerospace systems. Simulations were mainly performed by the novice designers under guidance and advisory support from other members. As a business consultant and architect into the lean PLM transformation, it was possible for the author to prototype additional constructs and functionalities by leveraging customized instances of the existing operational PLM virtual product management platform.

The study consists in a pilot implementation of the proposed methodology through the exploration of three design alternatives of an aircraft pylon. The three architectural options primarily refer to the range of options available for the engine firewall design. This is a reduced number of architectural options selected for the pilot study as the firewall options combined with options from the surrounding systems normally result in more architectural options available for evaluation. A preliminary elimination process was performed by the team of experienced engineers to focus on the simulation of three competing AOs following the CCS approach, which is the subject of Descriptive Study II. It should be noted that the aircraft pylon data expanded upon in this study is cleared from all intellectual property (except for Polytechnique Montreal), export controls and controlled goods content.

The first part of the chapter characterizes firewalls and the requirements for their design. The second part sets the context for the simulation by presenting the architectural options being considered as well as the selected PLM system off the shelf constructs when equivalence was found with the CCS model constructs. The third part then discusses results from the simulation, followed by a conclusion which summarizes the findings and limitations.

6.1 Aircraft engine firewalls

According to FAR 25.1191 (FAA, 2016), aircraft engine firewalls must be fireproof, designed and constructed so that no hazardous quantity of air, fluid or flame can pass from the pylon to other parts of the aircraft. Figure 6.1 illustrates a firewall design in which the artefact acts as a barrier between the engine and fuselage moving inbound.

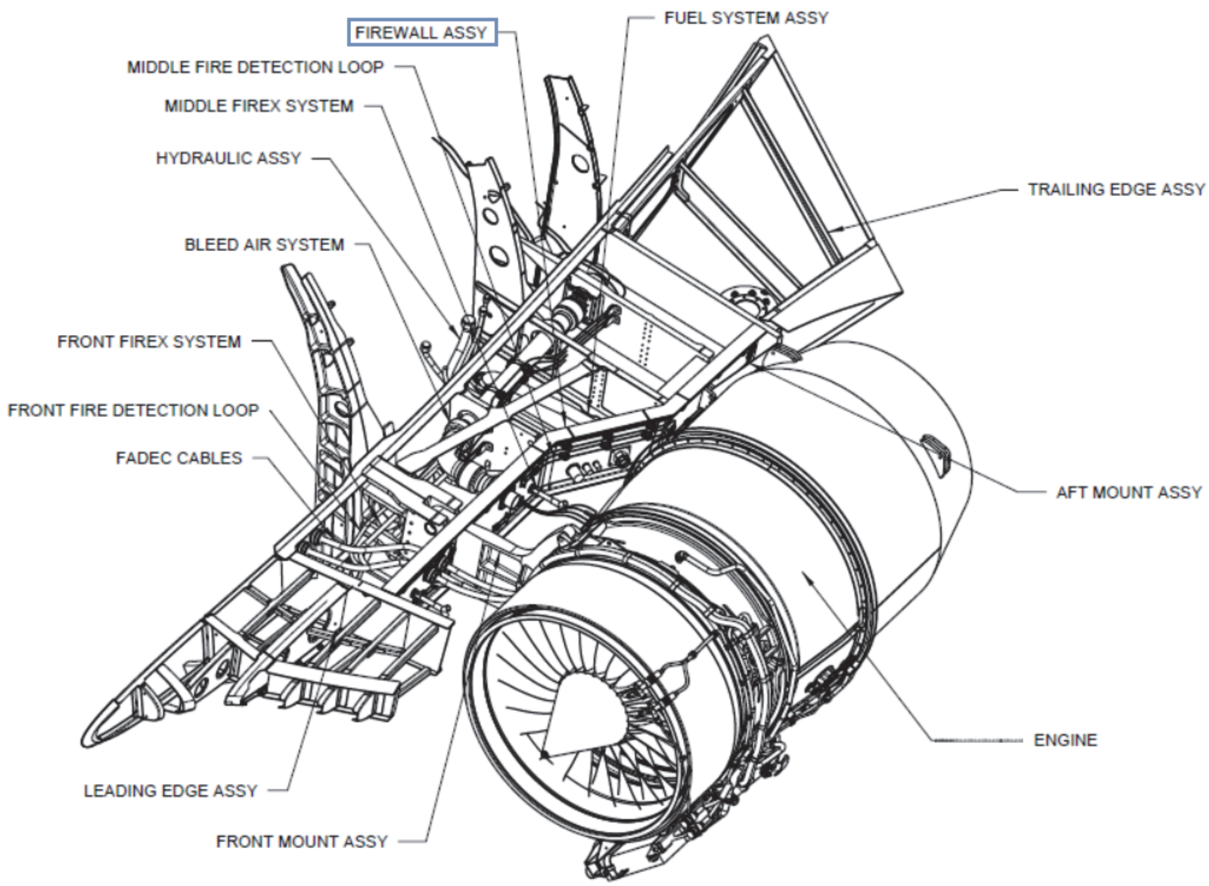


Figure 6.1: An aircraft engine firewall design

Firewalls must be sealed with fireproof, vapour and fluid tight fittings while also being protected against corrosion. Indeed, firewall components must meet numerous certification requirements by minimizing the fire zone and acting as structural parts in sections where they can be subjected to structural loads. The minimum thickness of the firewall is therefore driven by its structural requirements too, as it may transfer loads from the aft engine mount to spars within the pylon. This necessitates finite element analysis (FEA) and eventual physical testing to determine an optimal thickness that can insure withstanding the load accurately while being as light as possible. Based on above compelling requirements, firewalls are usually machined in titanium alloys and the part count is reduced to the maximum to comply with design for manufacturing requirements. Firewall design considerations also include aircraft and engine maintenance. For example, it must be possible to remove the forward engine mount without removing the whole firewall. This may justify the use of detachable sections in the firewall design in order to ease disassembly and removal of the forward engine mount.

As shown in Figure 6.2 below, firewall components play an important role in successful pylon systems integration. They constitute most of the systems interface, including interfaces with hydraulic system, fuel, bleed air system, fire extinguishing system (FIREX), fire detection loop and the electrical power system.

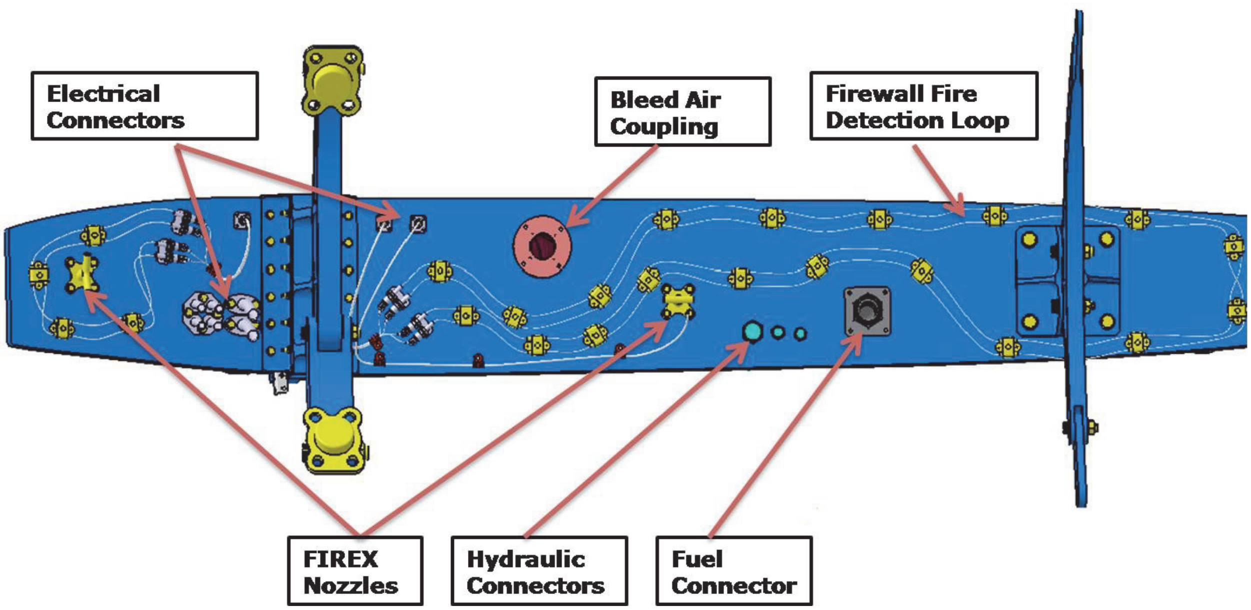


Figure 6.2: A firewall design with systems interface

Firewall design must therefore be performed in accordance with interfacing systems design. These systems are designed by quite distinct disciplines (hydraulics, fire protection, electrical etc.) which may respond with different design alternatives depending on the range of options available for the firewall design. This is the reason why firewall was selected as an appropriate candidate for validating how different set of options, including manufacturing/maintenance options, can be combined within the CCS approach in order to allow stakeholders to communicate and explore the design space on the basis of a range of design alternatives at a single point in time.

6.2 Simulation scenario and context

Three firewall design concepts are considered for the study. They conceptually have different outcomes in terms of fire protection, firewall and systems weight, accessibility/maintainability and manufacturing cost. The first concept presented in Figure 6.3 is a straight firewall concept as it follows a straight line that represents the shortest route between the two limiting fuselage stations. This option holds the advantage of potentially reducing weight to its maximum while leaving a fair amount of space between the fuselage and firewall for ease of access to systems (to be confirmed through simulation, prototyping and test).

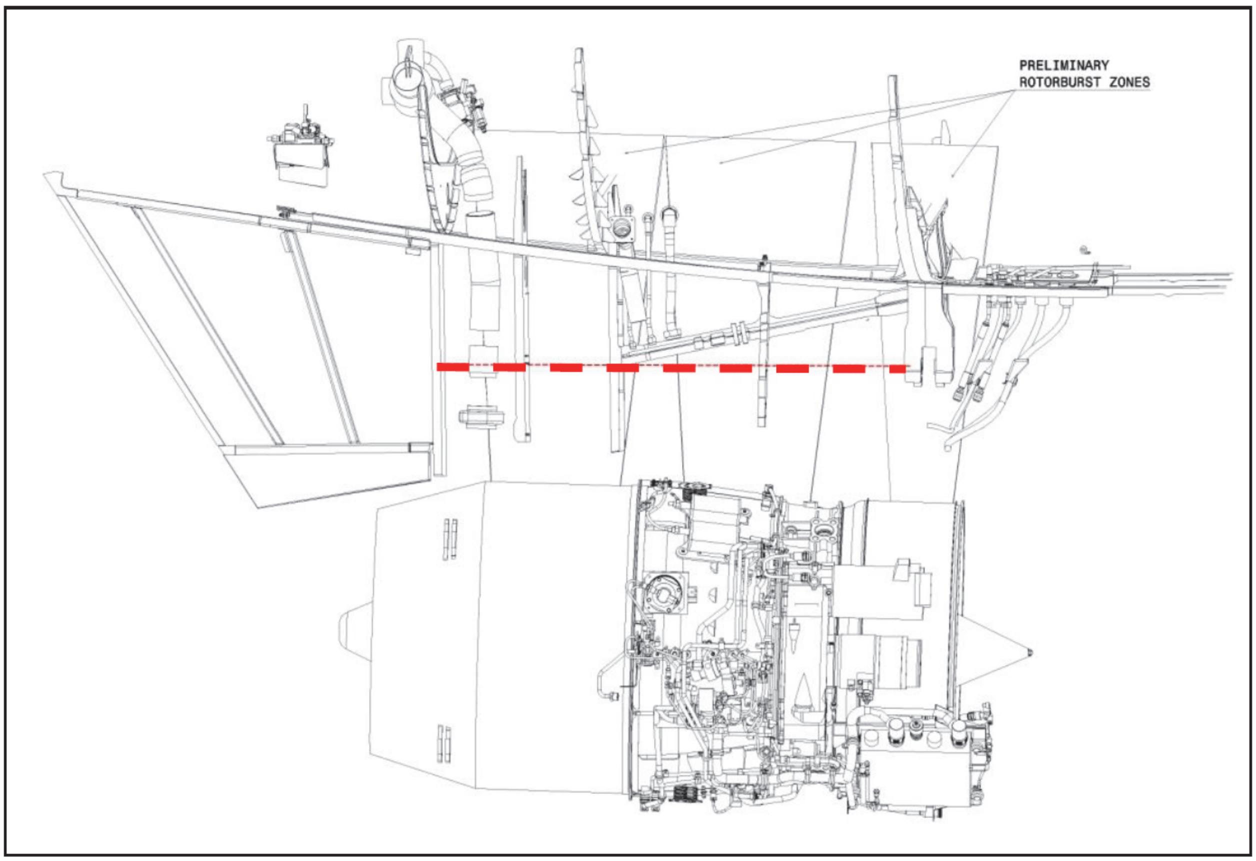


Figure 6.3: Straight firewall concept

The second concept presented in Figure 6.4 is a deflected firewall concept as it uses two inclined walls to reduce the risk that stress in the pylon might cause deformation of systems interfacing at the firewall. Compared to the straight firewall, a deflected firewall concept increases the length and potentially weight of the firewall while also leaving less space for accessing the systems. However, the negative impacts might be alleviated by the fact that the volume between the engine and firewall is increased, therefore inherently reducing temperature at the firewall. From a systems integration standpoint, slopes in the firewall may require, for example, bending the fuel, hydraulic, FIREX and bleed air lines while staying in corner radii that avoid turbulent flow. Firewall slope angles therefore become key parameters, especially in the case of bleed air, as they may lead to different diameter/radii of the duct compared to the previous concept. An appropriate insulation thickness may also be different, according to the selected diameter/radii.

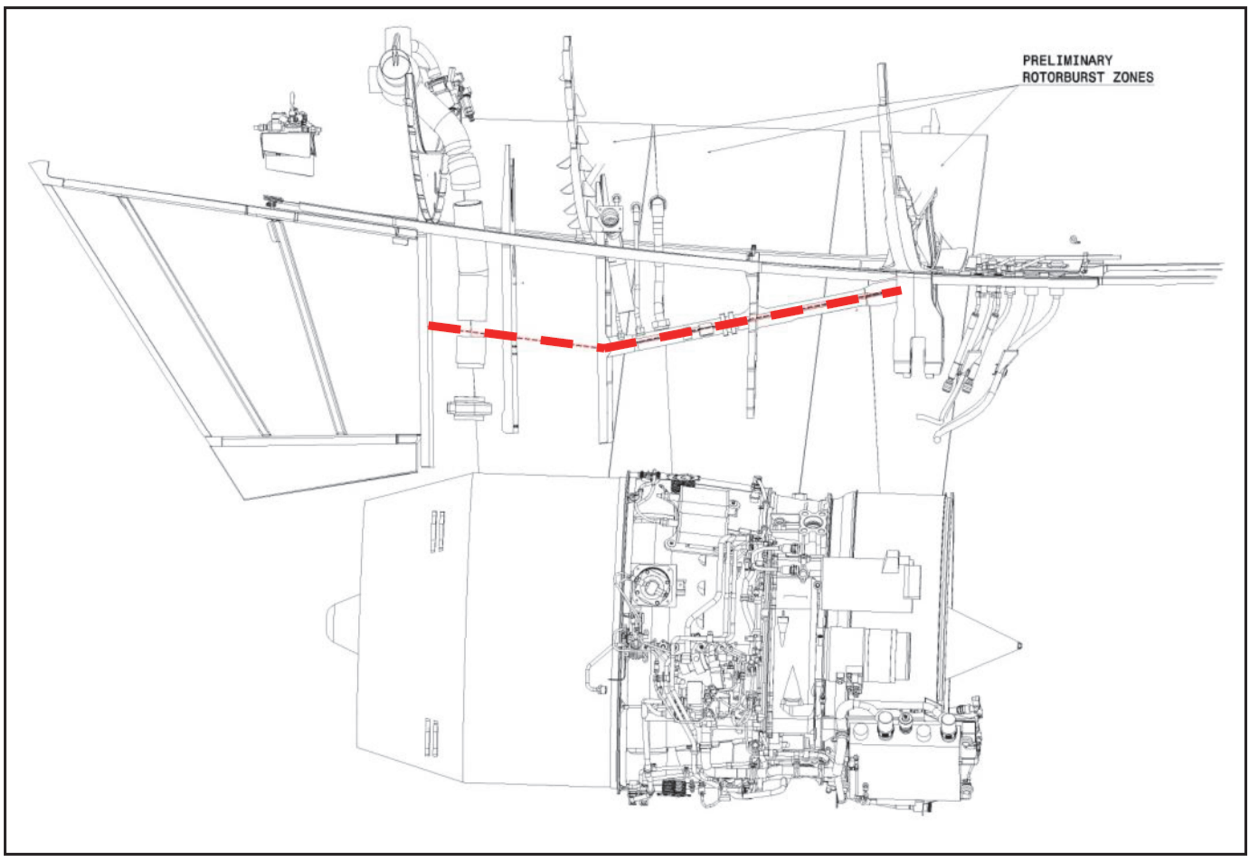


Figure 6.4: Deflected firewall concept

The third concept presented in Figure 6.5 is one slope firewall concept which extends previous forward slope up to the aft station limit. While this concept increases space between fuselage and firewall by also protecting a larger portion of the bleed air pipe, it increases proximity with engine hot sections, therefore potentially necessitating increased thickness of the firewall on the rear side. Similarly to the previous concept, a slope in the firewall may require further bending of the FIREX and bleed air lines while staying in corner radii that avoid turbulent flow.

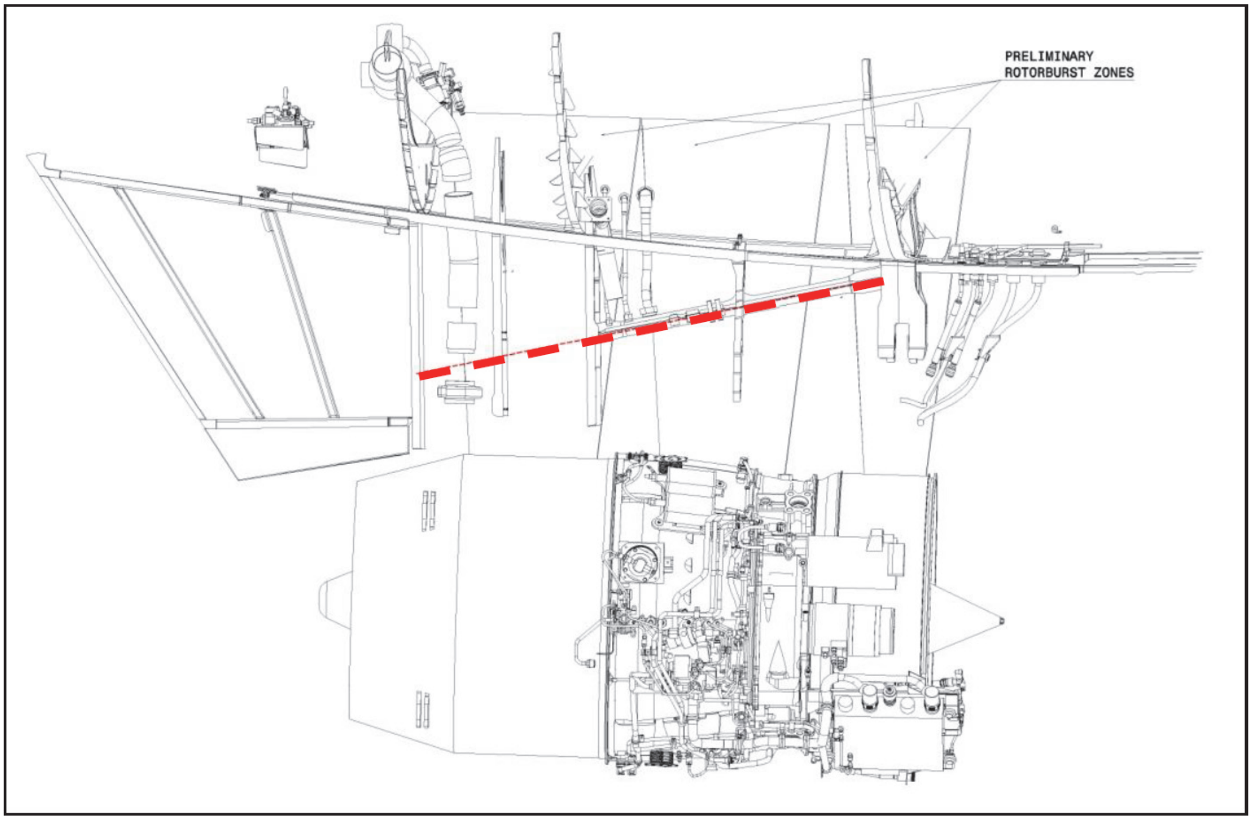


Figure 6.5: Slope firewall concept

The concepts as defined form the three architectural options that should be explored in parallel by simulating the CCS approach to product modelling for SBCE in a lifecycle management perspective. The PLM system in use at the company is Dassault Systemes 3DEXPERIENCE platform. 3DEXPERIENCE including CATIA is Dassault Systemes' platform solution for 3D Design, 3D digital mock-up collaboration, product data management and product lifecycle management. This platform has a business object and policy oriented framework like the vast majority of PLM systems and it implements most of the generic PDM, PLM and CM notions, functionalities and rules described for example in (Crnkovic, Asklund, & Dahlqvist, 2003; Watts, 2012). Some fundamental notions, functionalities and business/system rules within PLM-driven product development contexts are next described to clarify the meaning of recurrent terminology used in the context of the simulation.

BOM

A Bill of Materials in the context of the simulation is the hierarchical breakdown of a top level item into sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture an end product. No physical dimension is described in a BOM; however the rough outline includes the BOM Level, Part Number/Name, Description, Quantity, Find Numbers, Unit of Measure, related specifications, BOM Notes, etc. BOMs in the simulation are synced with their corresponding DMUs that support 3D modelling, FEA, FDMU, virtual prototyping and virtual factory simulations.

Build Unit

An object which represents actual development or Production engines with their serial numbers. Build Unit revisions represent different builds for the same development engine serial number and should also typically represent progressive updates for an engine in service.

Change

In Configuration Management (CM), a formally recognized modification/revision to a specified and documented requirement or to product definition data. It is also used to describe the formal change paper which authorizes the modification/revision to product definition data. In Manufacturing Operations, it's the modification of the hardware to incorporate the results of revised product definition data or it is simply the modification of the specified and documented manufacturing process.

Change Control

The processes and procedures which ensure that release product definition data is not modified/revised without appropriate change authority.

Clone

Operation to reuse data asset from existing artefact. An editable duplicate of an object, which may carry over object attributes and relationships.

CM

Configuration Management: A process for establishing and maintaining consistency of a product's performance, functional, and physical attributes with its requirements, design, and operational information throughout its life.

Configuration

A relative and coherent arrangement of hardware and/or software that together satisfy an end-use function.

Configuration Feature

A concept/object representing a product design feature that has options e.g. Feature = Color. This is an implementation of the notion of parameter found in generic product structuring (GPS) and CCS.

Configuration Option

A concept/object representing a design option which can be associated with specific part(s) or logical features distinguishing them from the others e.g. Options = Blue, Red, Green. This is an implementation of the notion of parameter value found in generic product structuring (GPS) and CCS.

Configured Part

A part containing children parts that can be filtered "in or out" based on individual part effectivity expressions. A part for which a change to the content children i.e. recipe, does not require its re-identification. This is a terminology used in some PLM systems for configurable items as described herein.

ECM

Enterprise Change Management: A single standardized, global, and closed-loop change control process for product related data i.e. closed-loop process for change assessment and change propagation that includes interconnected objects such as Issue, Change Request (CR), Change

Order (CO), Change Action (CA), Manufacturing Change Order (MCO), Development Change Order (DCO) and Service Change Order (SCO).

Effectivity

An expression associated to an item in a configurable logical structure or BOM/DMU that determines the conditions for which the logical feature or part/3D part is "in or out".

GBOM Link

A view showing a link between a logical feature and part object, which represents the design solution for that feature/system component. This is an implementation of the **gbom** relationship found in CCS as adopted from GPS.

Hardware Product

A hardware product is the digital object that identifies the product or product platform engineered to current or future orders. In the context of the simulation, the aircraft pylon, including all available architectural options, represent the hardware product.

Hardware Build

Hardware Build is the identification of a specific piece of hardware assigned to a Build Unit. Hardware Builds are identified with Serial numbers and they help with hardware traceability within engine configurations.

Lifecycle

A series of states through which an object goes during its existence. Each state allows or restricts for specific capabilities and modifications to be made to the object. This is governed by the object policy

Logical Feature

An object that represents a system component in the logical structure based on its function and location within the product. LF acts as a link between a requirement and a part which satisfies that requirement. This is an implementation of the typical technological domain construct i.e. functional feature/logical feature found in product modelling representational formalism as adopted in CCS.

Logical Structure

Systems engineering view of the product / functional breakdown of engine components represented by logical features.

Model

A model object represents a specific type design that can be offered to customers in a certified range of variants. It is usually associated to its corresponding hardware product versions and derivation chain.

Object

A PLM system element that users interact with to perform work, for example, a part or document. Each object type comes with specific attributes, lifecycle, the ability to connect with other objects, etc.

Part

Design solution identified with a part number.

Part Policy

A set of rules that governs the behavior of a part object e.g. configurable, concept or Change controlled policy.

Part Specification

A specification object, which can include different types of documents a user wants to connect to the part object, by using a specification relationship. Refers to controlled and uncontrolled specifications e.g. internal specs, AMS, ANSI, MIL specs, etc.

Policy

A set of rules that govern the behavior of an object at each stage of its lifecycle, including who can access and modify it as well as the type of transaction that can be performed e.g. ability to modify specific attributes, promote/demote lifecycle states, connect with other objects, etc.

PLM

Product Lifecycle Management: a concept for the integrated management of product related information through the entire product life.

Product Configuration

An object that captures the set of rules and selections for generating or filtering a structure for a specific configuration. This is a generic PDM configurator mechanism that allows for setting parameters, parameter values and constraints for filtering coherent configurations as defined in CCS and adopted from GPS. The product configuration as set up in a PLM system becomes an easy and reusable token for all stakeholders across the enterprise for retrieving the corresponding architectural option (AO) or product configuration (PC) as discussed in CCS. In the context of the simulation, product configuration can be applied to configurable structures such as BOM, DMU and logical structure.

Relationship

The connection between objects. For example, an eBOM relationship connects two parts together as parent/child. Each relationship type has a defined cardinality for each side and it comes with specific attributes.

Route

A workflow artefact through which a notification is transmitted or an approval to promote and object is obtained.

6.3 Conducting the simulation

The simulation is enabled by first setting up all participants' accounts, accesses, profiles (licences), roles (product manager, system engineer, designer, manufacturing engineer and development engineer) and security levels, which in this case are very less restrictive as a dedicated vanilla environment with no sensitive data is given to the team for the simulation. The simulation is then initialized by importing data from an old pylon design which serves as past project data for which reusability is explored while introducing three new separate concepts for SBCE exploration. This past project data is in the form of native CAD definition as shown in Fig. 6.6.

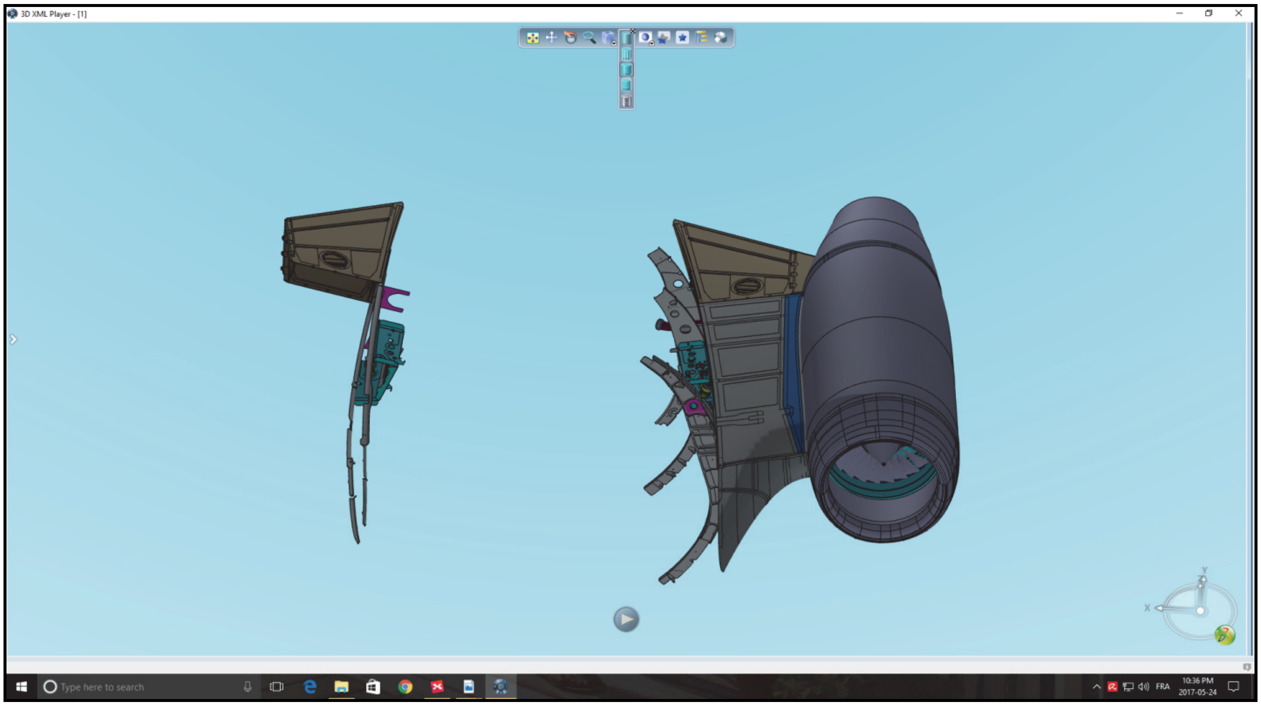


Figure 6.6: Legacy dataset for the simulation

The DMU package is loaded in the simulation environment using off the shelf data import tools with the help of the CAD/DMU specialist. Only the pylon, engine, nacelle and non-sensitive data are imported in the environment for intellectual property and confidentiality reasons. Once complete, the old pylon data is available in the PLM system in the form of a BOM and DMU with corresponding granular objects that can be reused in a new development project. This provides the realistic context for the participants to commence the simulation.

6.3.1 Working in the technological domain

Modelling functional requirements i.e. Requirement Specification (RS) tree and functional couplings (**fc**, **ic**) is not included in the scope of the simulation as the focus of this simulation is less on the functional-technological co-evolution process than the portion of the CCS product modelling approach that allows various disciplines involved in the product lifecycle to consider sets of distinct alternatives concurrently, representing whether single product or product platform design bandwidth. The team therefore start their exploration of the design space by leveraging the legacy pylon architecture (physical) to lay out a new logical structure while introducing options as described in 6.2. These options are defined by following the CCS approach in the technological domain, which is basically about using logical feature constructs (LF) and assigning parameterized effectivity expression to each design option within the explicit logical structure. This work is performed by participants with system engineer roles as, during product development, they are the ones holding the knowledge about the product architecture, modularity, scalability and correspondence with the requirement specifications (see **sb**, satisfied by relationships). The system engineer role is also entitled to define test cases and the means by which a design solution (e.g. Part) embodying the logical feature (**gbom**) must be verified against the specification or beyond. Figure 6.7 illustrates the resulting explicit structure within the technological domain.

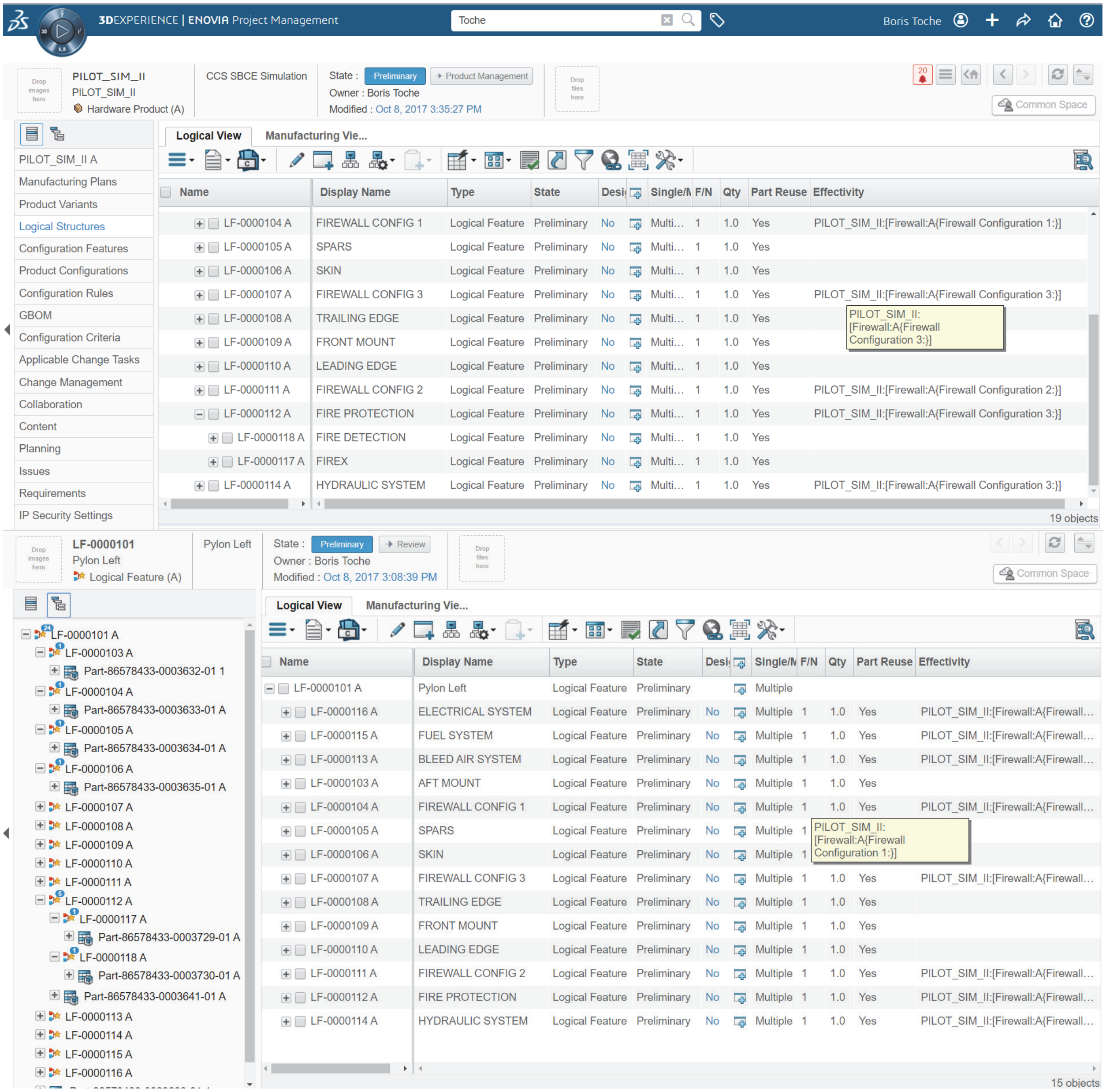


Figure 6.7: Explicit structure within the technological domain

All participants can filter the explicit logical structure at any given point in time and by using a Product Configuration (PC) token that contains the combination of valid parameters (Configuration Features) and parameter values (Configuration Options). This generates a coherent architectural option (AO) in the technological domain. The filtering mechanism allows participants to concurrently work on the basis of the range of available conceptual design alternatives and to progressively document each of them as data and knowledge about the design become available. Figure 6.8 shows the three design alternatives formulated into PC rules as well as one coherent product variants filtered by using the corresponding PC token.

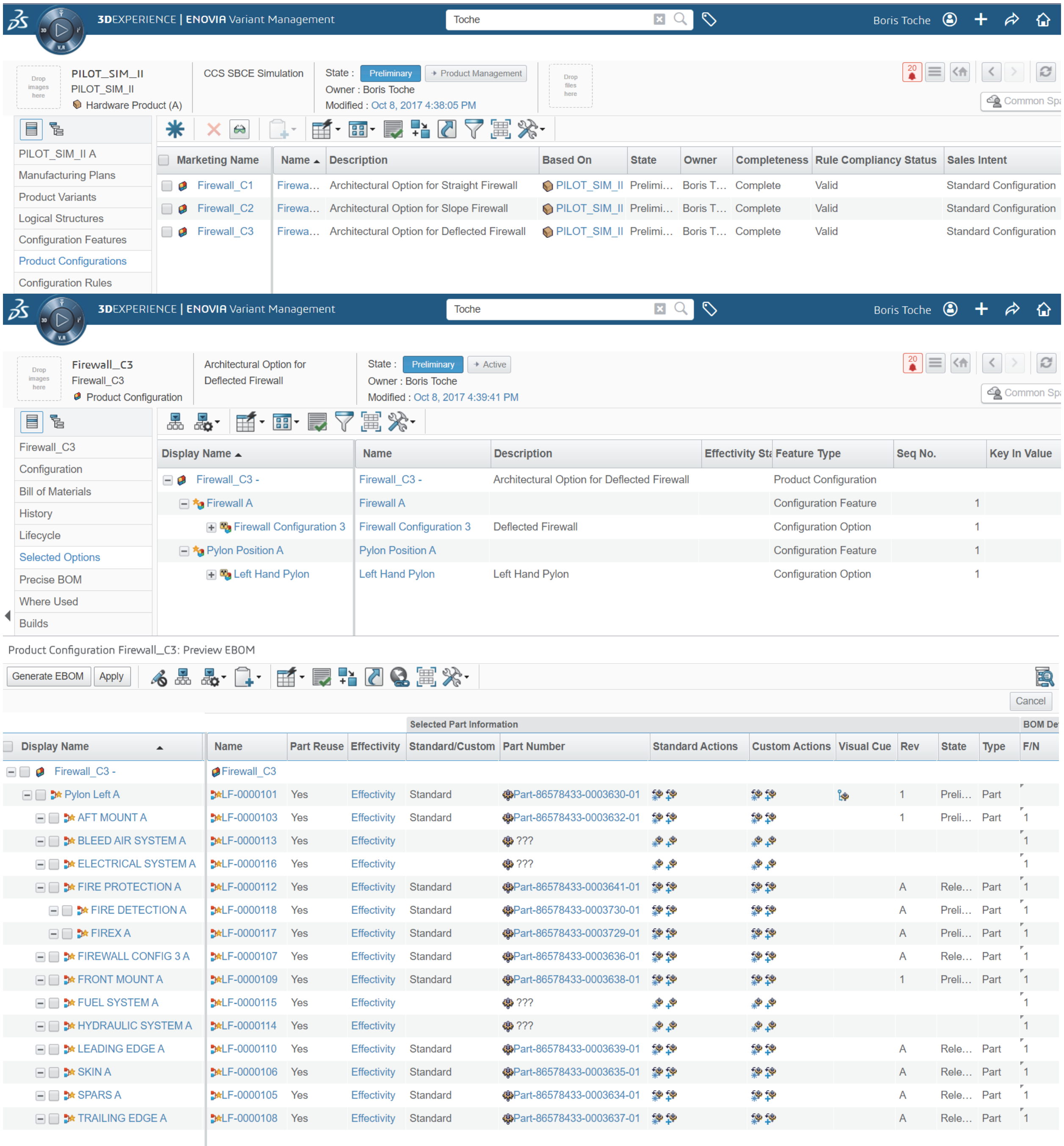


Figure 6.8: Product configuration filtered within the technological domain

It should be noted that participants with system engineer roles can also be designers, advance design engineers or people with configuration management background who are simply given the role of system engineer too. This is done because they have such skillset to perform various tasks in a multi-domain framework by also understanding architectural variability and configurability within the product. Indeed, system engineers play a key role in early phases of product development because they hold the knowledge and skills to interpret and translate requirement specifications into logical constructs (systems), therefore bridging between the functional and technological domains. They may additionally bridge between the technological and physical domain by assigning/reusing physical embodiments through the **gbom** relationship. Reuse typically happens when existing design solutions (e.g. Part) can readily be assigned to a new logical feature or when existing logical feature is added which already contains one or more validated design solutions. However, in case new physical design is required, one would typically expect a participant with designer role to link his/her output to the logical feature by using the same **gbom** relationship. The designer may not have system engineer skills/role and it might therefore be required for a system engineer to validate the association and eventually assign **gbom** effectivities according to parameter options the new design solution is expected to meet. The logical feature is therefore the main shackle that allows for systems engineering and design engineering connectivity in order to instantiate variants in the physical domain. It also enables traction for proper V&V by linking between the requirements, system decomposition, design solution and design substantiation. Figure 6.9 illustrates a catalog of parts available in a logical feature for instantiating product variants. The gbom links are parameterized by Configuration Features and Configuration Options so that the appropriate design solution (Part) is selected while instantiating an AO with the corresponding criteria.

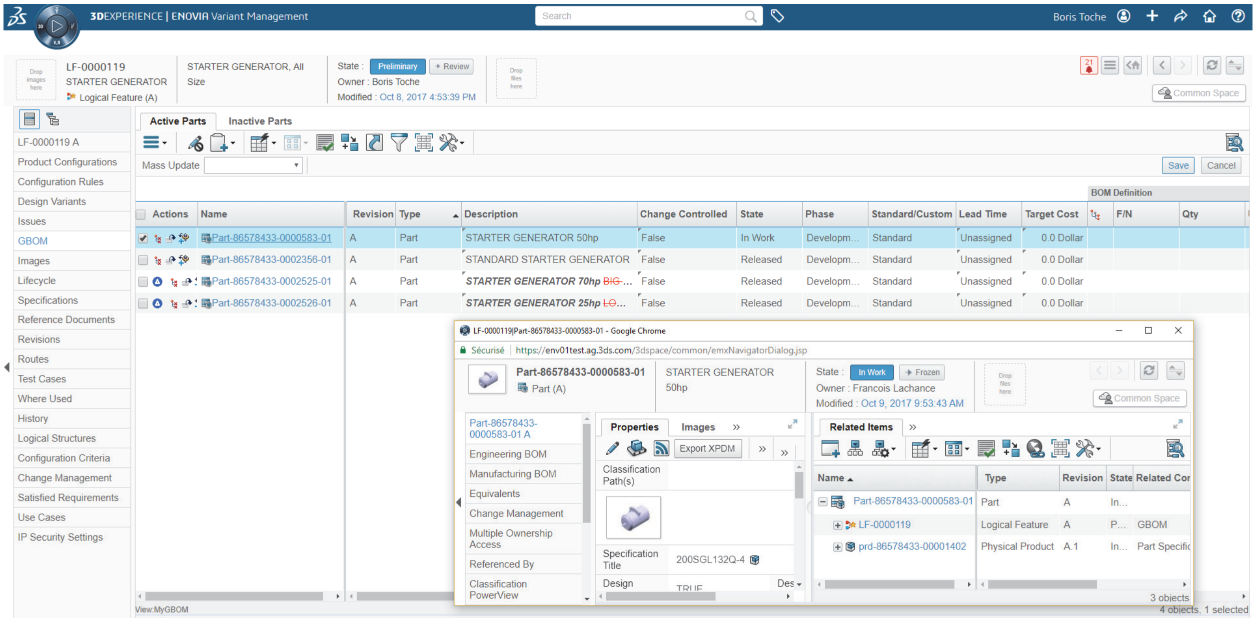
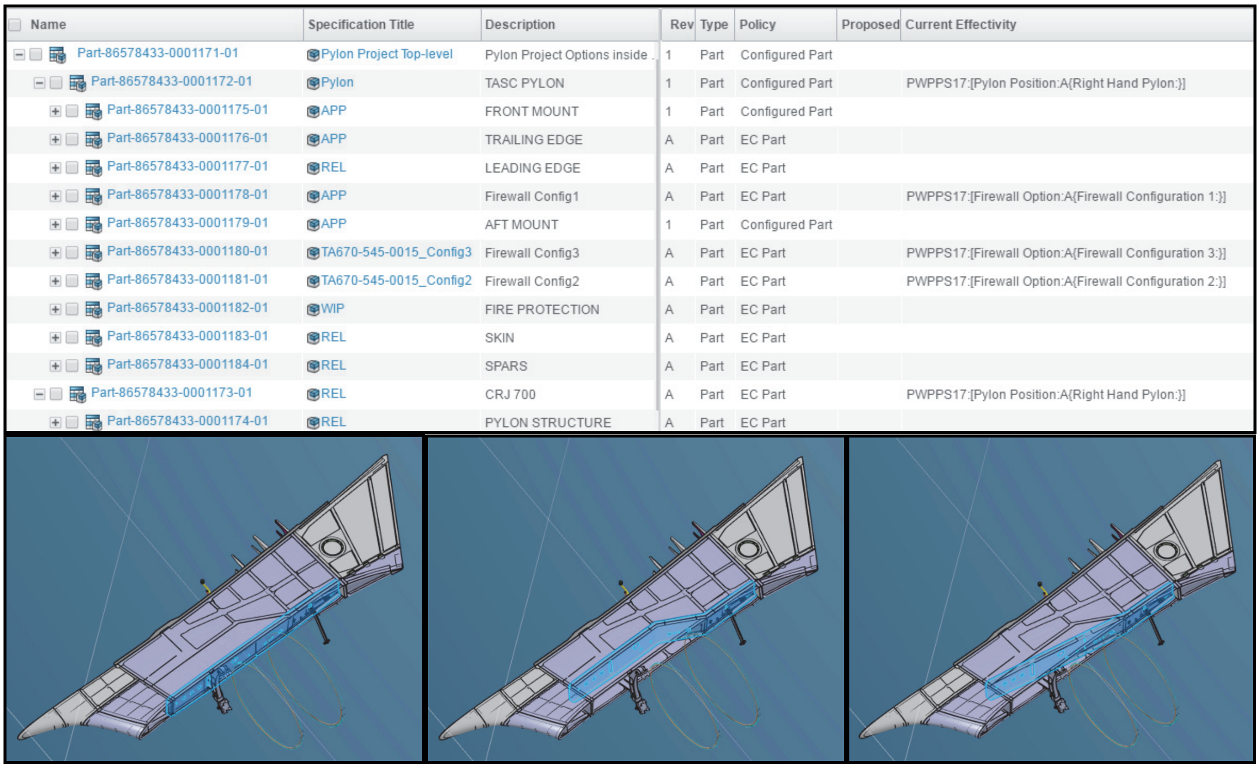


Figure 6.9: GBOM catalog for a logical feature

One may argue that firewall design options simulated herein are rather about scalability than modularity because the technology or logical system i.e. structural firewall used to meet the fire protection requirement is the same in the three options. This is to say, the three options should be maintained based upon **gbom** effectivities in one single logical feature (scalability) rather than **lf** effectivities for three different logical features (modularity). Such position is not valid because scalability is the variability of design parameters e.g. length, size to meet specific customer requirements whereas modularity is interchangeability between design solutions that provide different properties of the product without affecting its baseline architecture (Johannesson et al., 2017). The last fits better with the three firewall concepts as they result, for example, in different fire protection, accessibility and maintainability outcomes for the same pylon body. Hence, the reason why in the current simulation, the set of alternatives considered for the firewall and interfacing systems is represented with modularity within the technological domain.

6.3.2 Working in the physical domain

Engineering disciplines use BOM/DMU views to filter the range of available AOs in order to perform each necessary embodiment, FDMU and virtual prototyping simulations in accordance with the amount of data required to inform the set-based elimination process.



Name	Specification Title	Description	Rev	Type	Policy	Proposed	Current Effectivity
Part-86578433-0001171-01	Pylon Project Top-level	Pylon Project Options inside .	1	Part	Configured Part		
Part-86578433-0001172-01	Pylon	TASC PYLON	1	Part	Configured Part		PWPPS17:[Pylon Position:A{Right Hand Pylon:}]
Part-86578433-0001175-01	APP	FRONT MOUNT	1	Part	Configured Part		
Part-86578433-0001176-01	APP	TRAILING EDGE	A	Part	EC Part		
Part-86578433-0001177-01	REL	LEADING EDGE	A	Part	EC Part		
Part-86578433-0001178-01	APP	Firewall Config1	A	Part	EC Part		PWPPS17:[Firewall Option:A{Firewall Configuration 1:}]
Part-86578433-0001179-01	APP	AFT MOUNT	1	Part	Configured Part		
Part-86578433-0001180-01	TA670-545-0015_Config3	Firewall Config3	A	Part	EC Part		PWPPS17:[Firewall Option:A{Firewall Configuration 3:}]
Part-86578433-0001181-01	TA670-545-0015_Config2	Firewall Config2	A	Part	EC Part		PWPPS17:[Firewall Option:A{Firewall Configuration 2:}]
Part-86578433-0001182-01	WIP	FIRE PROTECTION	A	Part	EC Part		
Part-86578433-0001183-01	REL	SKIN	A	Part	EC Part		
Part-86578433-0001184-01	REL	SPARS	A	Part	EC Part		
Part-86578433-0001173-01	REL	CRJ 700	A	Part	EC Part		PWPPS17:[Pylon Position:A{Right Hand Pylon:}]
Part-86578433-0001174-01	REL	PYLON STRUCTURE	A	Part	EC Part		

Figure 6.10: Explicit structure within the physical domain (BOM/DMU)

Figure 6.11 below illustrates the explicit structure filtered within the physical domain, in this case the DMU view.

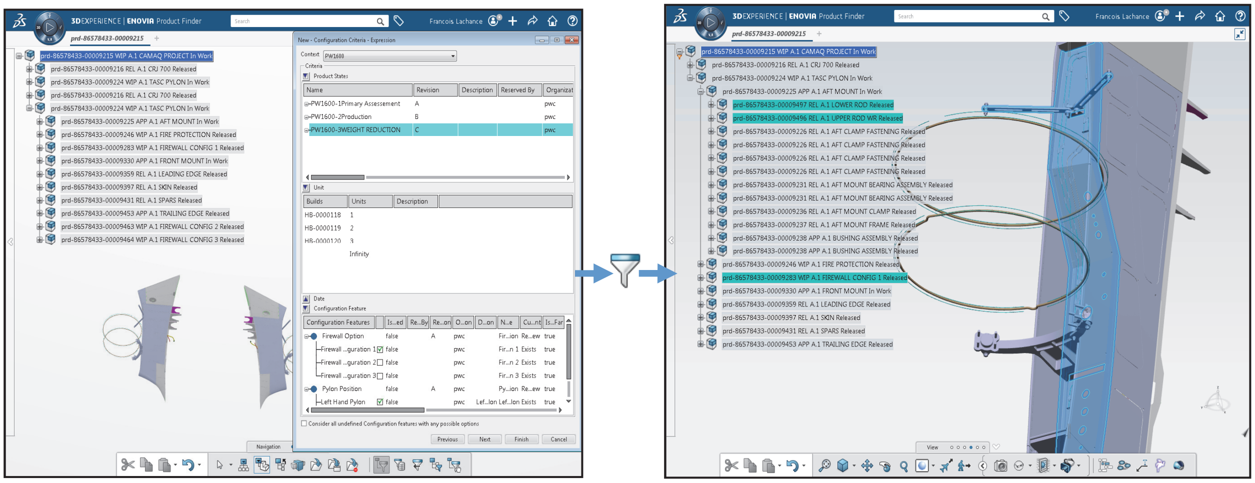


Figure 6.11: Explicit structure filtered within the physical domain (DMU)

Similarly, in parallel and on the basis of the same range of available AOs, manufacturing engineering explore each corresponding manufacturing process through virtual factory simulations. Figure 6.12 below illustrates manufacturing process options for a given as-designed configuration.

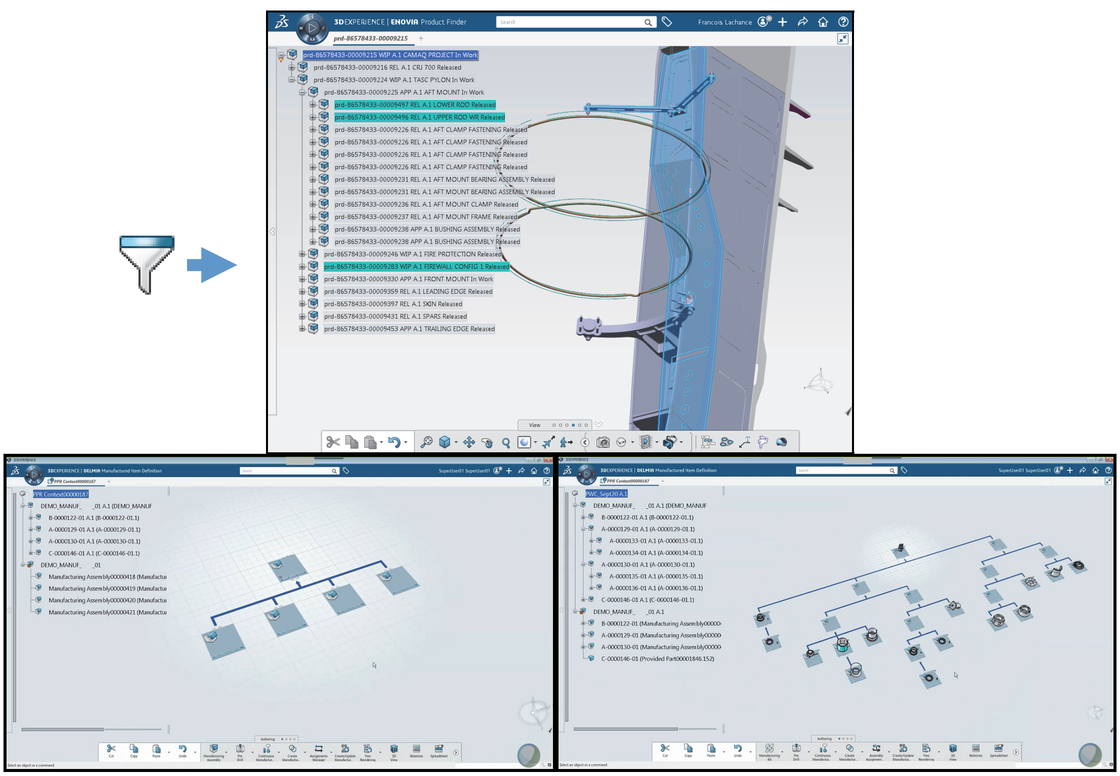


Figure 6.12: Manufacturing process options for a product configuration (as-designed)

Multiple disciplines are therefore overlapping their own solution options with other discipline options by communicating on the basis of a range of available alternatives as deployed within the environment in conformance with the CCS approach.

As time progresses, data is gathered which may lead to enough information to eliminate one or more AOs. For instance, assuming a fire zone as a region which contains a potential source of ignition and where flammable liquid and/or vapour leakage can occur, firewall constitutes a limit of the region. As such, firewall must be shaped and positioned so that the air flow within the fire zone is the least obstructed and the volume of air within the zone is kept to a minimum to ensure most adequate concentration of fire extinguishing (FIREX) agents. In the context of the simulation and, as illustrated below with virtual prototyping, the engine hot section (B1, B2) and engine accessory compartment (B3) shall be designated as fire zones. In all design concepts, the volume between the nacelle, engine and pylon is further separated into two distinct zones by the front mount yoke since in the event of a FIREX agent discharge, the yoke will limit propagation of the agent from one zone to the other. These aft (A1-A4) and front (A5) fire zones extend up to the firewall.

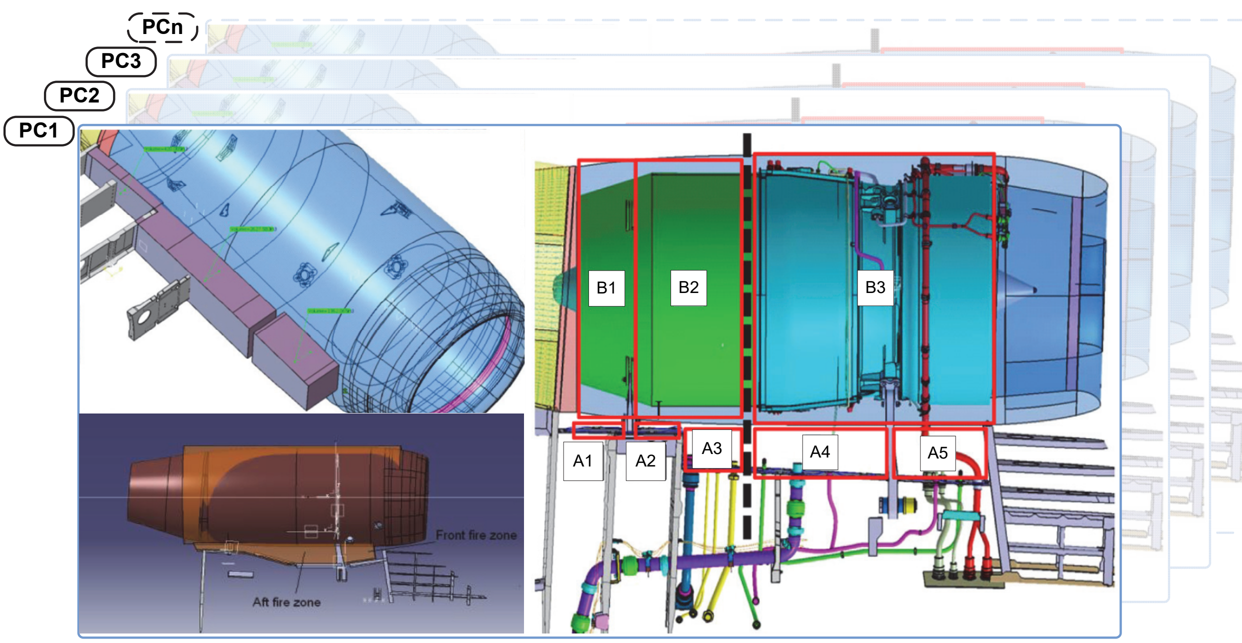


Figure 6.13: Virtual simulation of fire extinguishing agent discharge for multiple concepts

Virtual prototyping simulations of the discharge of fire extinguishing agents for each AO provide key information for the set-based selection process without resorting to physical testing. For each available concept, it is possible to simulate the distribution of FIREX agent according to the air flow in each area and also calculate the concentration of agents in the fire zone volumes that result from the structural arrangement i.e. configuration under consideration. This allows for a set-based comparison while also maturing the design as it may pertain to all options e.g. splitting the FIREX flow in two, one of around 33% for the front fire zone and another of 66% for the aft fire zone, as the last is similarly larger in all cases. Then there might be different extinguishing or discharge approaches, nozzle types and quantity of agent required for each configuration. Such bandwidth represents the FIREX discipline set of available options which is overlapped with others and simulated in the virtual space by representing each design alternatives following the CCS approach. Figure 6.14 shows accessibility/maintainability overlapping their options by filtering and assessing each available design alternative in order to inform the set-based elimination process. Instead of tedious manipulation of mannequins in the virtual environment, more advanced and easier simulations can be performed by using virtual reality glasses available to Information Technology at the company. It was unfortunately not possible to do so during the pilot simulation because the equipment was allocated to a project with higher priority.

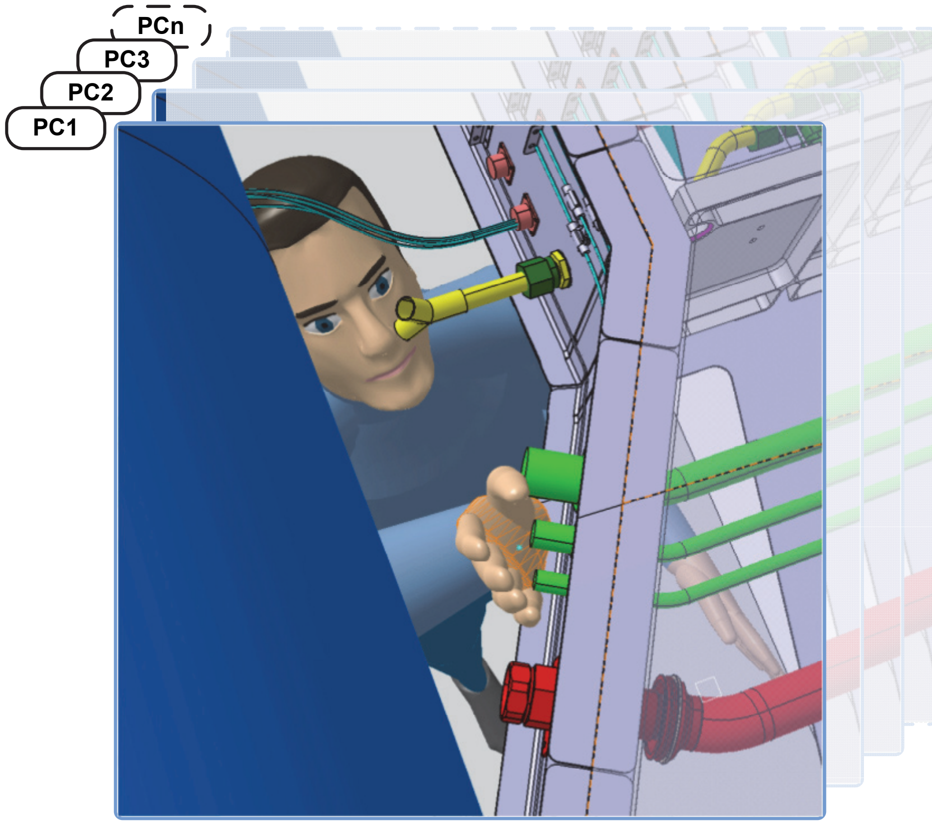


Figure 6.14: Virtual simulation of accessibility and maintainability for multiple concepts

It is therefore possible to compare the three alternatives based upon criteria stipulated in section 6.2, this by weighing them according to a ranking of the criteria from the most to the least important in the context of the development program. As discussed in chapter 5, a number of comparison matrices, grids and tools are available in the literature to select from for this purpose. An example of trade-off curve that can be generated from the study is the FIREX agent concentration for a given timeframe and per volume of fire zone. This trade-off curve would combine results for various volume, nacelle air flow and agent discharge pressure (all constant in the figure below).

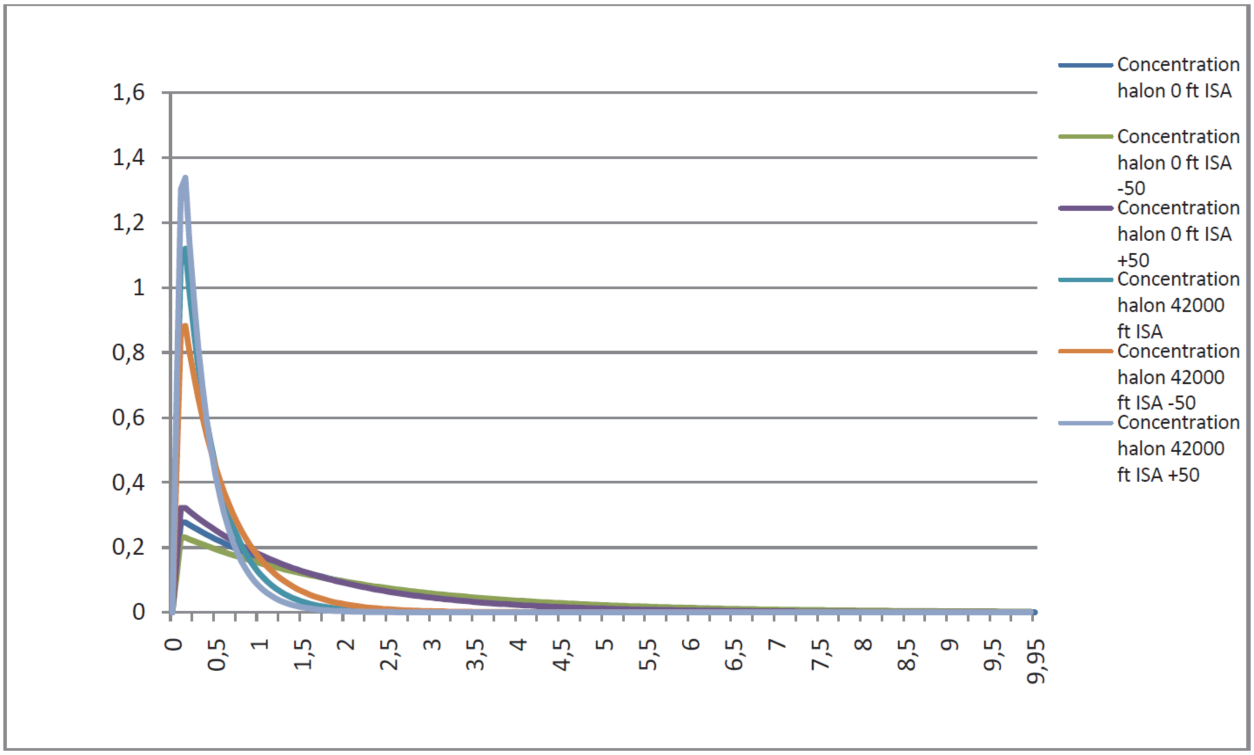


Figure 6.15: Concep#2 FIREX agent volumetric concentration vs. elapsed time (by ISA altitude)

To elaborate, MIL-E-22285 (1959) requires that "actuation of the extinguishing system shall produce a concentration of agent at least 6% in all parts of the affected zone. This concentration shall persist in each part of the zone for at least 0.5 second at normal cruising condition" (Amended § 3.8). This specification is applicable to all firewall designs and, to that matter, a trade-off curve would more efficiently embed reusable knowledge for the next development programs. Discrete explorations based upon the study and simulation of specific alternatives allow to gather knowledge about specific areas of the design space. By interpolating between these areas, just like one would draw between two discrete points in a trade-off curve, it is possible to discover new combinations that lead to innovation. For example, the team mainly used virtual simulation of the CCS modelled design bandwidth to infer that an optimal design would be the combination of the straight and deflected concepts as it results in a low fire zone volume, compliant FIREX agent concentration in case of fire, ease of systems routing, accessibility and maintainability as well as an overall desirable weight, manufacturing and assembly costs. Such outcome is advocated in SBCE as a preferred global optima rather than independently optimized components (Sobek, 1996a). This global optima is more easily reached by communicating about sets of designs and design spaces, then narrowing and committing after establishing feasibility.

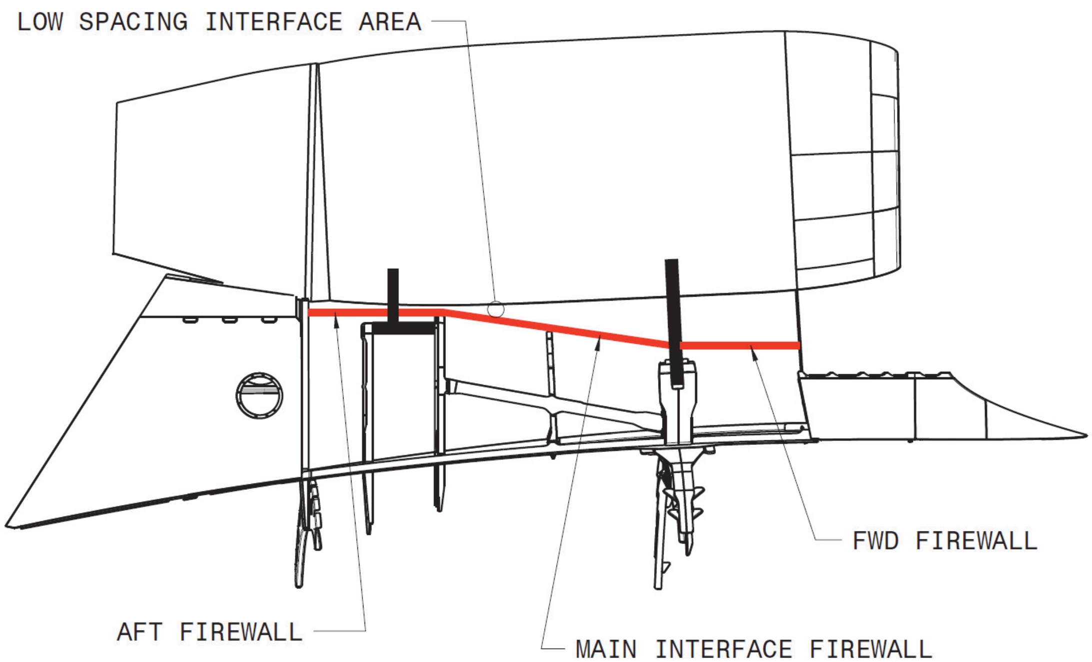


Figure 6.16: Optimal firewall concept converged from the design bandwidth

As the optimal design is also modelled and parameterized according to the CCS approach, it is important to note that all discrete concepts explored remain available within the framework for retrieval, audit and reuse based upon their PC token. From a product platform design standpoint, these concepts can be seen as valid product variants modelled and maintained as a product family across CCS multi-domain explicit structures.

6.3.3 Working in the existential domain

Depending on the amount of data that can be collected through virtual prototyping and virtual factory simulation, it may sometimes be necessary to build physical prototypes in order to gather additional data about a design to appropriately inform the set-based elimination process. It is also required by certification authorities to verify that, whatever design is selected, it complies with the regulations requirements. For these reasons, physical prototypes may be built for various competing alternatives and this is a must for the final design or for each variant that can be instantiated for delivery to a customer in the case of product platform design. Although it was not possible to build a physical prototype due to resources and time allocated to the simulation, physical prototype views were, however, deployed in the environment as part of the simulation in order to continually validate the CCS approach when it comes to the multi-domain connectivity and configuration tracking.

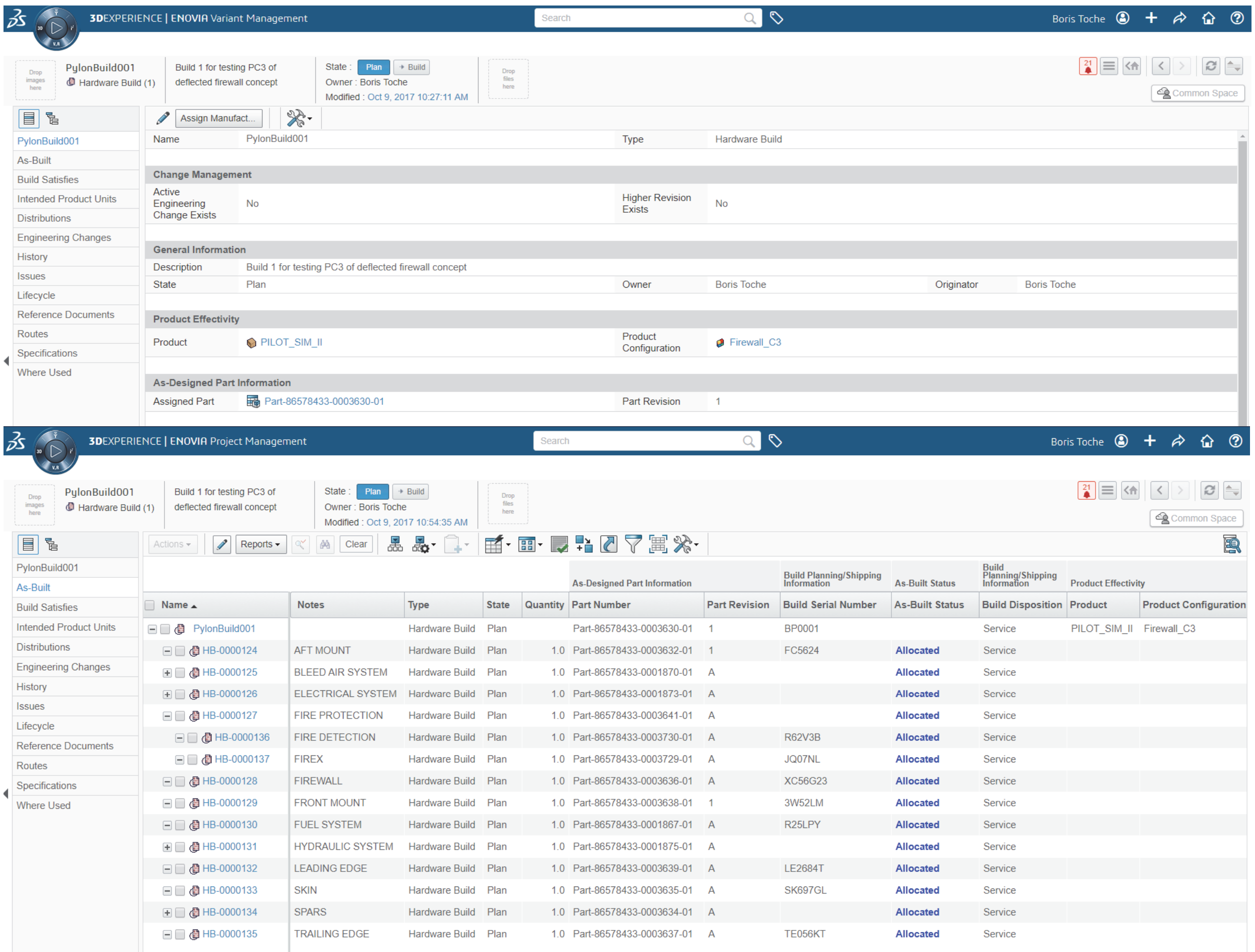


Figure 6.17: Instantiation in the existential domain - Build serial

As previously discussed, and especially in chapter 5, the required physical tests and procedures and derived as-tested product structures (or bills of materials) are not systematically connected to the as-designed structure and therefore their proper configuration management is not possible within common PLM environments. Consequently, hardware testing transactions and prototype information tracking are not addressed within common PLM solutions. These gaps remain present in the advanced version of the PLM system used for the simulation. It was therefore necessary to reapply customizations developed in Chapter 5 in order to allow transactions within the CCS existential domain. The remaining part of the simulation was identical to pilot simulation I in chapter 5 to the matter of physical prototyping and testing collaboration. Similar benefits of the approach were observed in addition to the connectivity between as-tested structures and corresponding AO configurations for an informed decision-making in the context of the CCS approach for set-based design.

6.4 Conclusion

A validation of the proposed Complementary Configurable Structures (CCS) approach was reported in this chapter. This simulation was performed in four months by a small team composed of the author, one system engineer, one development and test engineer, one product definition integrator, three designers (summer interns) and one CAD/DMU specialist. This was done as part of a special pilot evaluation for the lean PLM transformation of the configuration methodologies and supporting tools of a lean manufacturer of complex aerospace systems.

Typical off the shelf constructs and configurator of a conventional PLM system in use at the company were leveraged for the simulation. This platform has a business object and policy oriented framework like the vast majority of PLM systems and it implements most of the generic PDM, PLM and CM notions, functionalities and rules.

The study consisted in a pilot implementation of the proposed methodology through the exploration of three design alternatives of an aircraft pylon. The three architectural options primarily referred to a range of available options for the design of the engine firewall.

Two limitations were found during the simulation. The first is the void in conventional PLM systems when it comes to CCS existential domain constructs and methodology. As-tested product structures (or bills of materials) are poorly addressed in common PLM solutions and they are not systematically connected to corresponding as-designed for their proper configuration management. Indeed, hardware testing transactions and prototype information tracking are not well addressed within common PLM solutions. This limitation was overcome by resorting to CCS bespoke functionalities for the existential domain, which are implemented by following the methodology already demonstrated in chapter 5. The other limitation is the inability of the system, as-simulated, to automatically convert the technological domain explicit structure (logical structure) into the physical domain (explicit BOM) so that the same AOs can be simultaneously filtered in the synchronized explicit BOM without having to duplicate the configuration effort. Off the shelf functionalities only allow to set **lf** and **gbom** effectivities in order to maintain the explicit structure in the technological domain, which is then used to instantiate resolved (100%) product variants in the physical domain i.e. new customer product instance. The new product variant can then grow into an explicit structure by representing and maintaining only change evolution effectivities within the structure. No customization was done to reflect CCS intended domain effectivities synchronization due to the resources and time allocated to the simulation. This should be done in future simulations to better reflect CCS model distinctive intent as well as overall resulting benefits.

Overall, the outcome of the simulation was positive, plentiful of observations and findings and, most of all, rewarding for the participants from a learning and educational standpoint. A comment worth citing is one given by the participant from advance design engineering, who mentioned that the approach would “help to see things differently in advance design but also at the enterprise level”. The participant with systems engineering skills, who spent the most part of his career in design engineering, mentioned that “the approach is beneficial for every designer and the community because all options a designer considers while solving a problem are available, documented and well organised for everybody to reuse them, whereas today, they stay buried in the designer’s own private folders past preliminary or critical design reviews”. The development/test engineer agreed with the statement by adding that he sees “huge potential in the approach because it improves collaboration between design engineering and development/test engineering but most valuable, it allows strong connectivity between the requirements, design solution and furthermore the means for verification.” Indeed, today, one in design engineering may remember a test that was requested by some colleague sometimes ago during a given project, but it would be very difficult both for them and development/test engineering to retrieve all information that tell the end-to-end story about this test i.e. the requirements Design was trying to meet, the test request, assumptions and approximations, as-designed configuration used for the test, as-tested configuration including as-built with serial numbers as ran in the test cell and ultimately, all results from the test gathered together. The CCS approach was also found during the simulation to enable a setting that promotes innovation. The team appreciated “getting into this mindset" of combining all possible options into a range of available design alternatives in order to carefully consider each and document them concurrently. All participants recognized that the approach, as deployed, was very effective for discovering new solutions by pushing the team to explore further and only commit once they have enough data to conclude about the weakness of a design. Such exploration opens the door to the discovery of unknown properties of a design, then the discovery of new solutions space by progressively combining options, which ultimately leads to innovation. Similar observations were made by Raudberget (2015) who recommended that further research should be done to understand and validate whether these improved innovation abilities are characteristic features of SBCE or simply the result of a smart team working together. This is difficult to clarify. However, it is argued here that there are additional evidences to believe that a context where SBCE is enabled, either by using spreadsheet-based morphological charts or conventional PLM framework components, is a context where innovation is likely to improve.

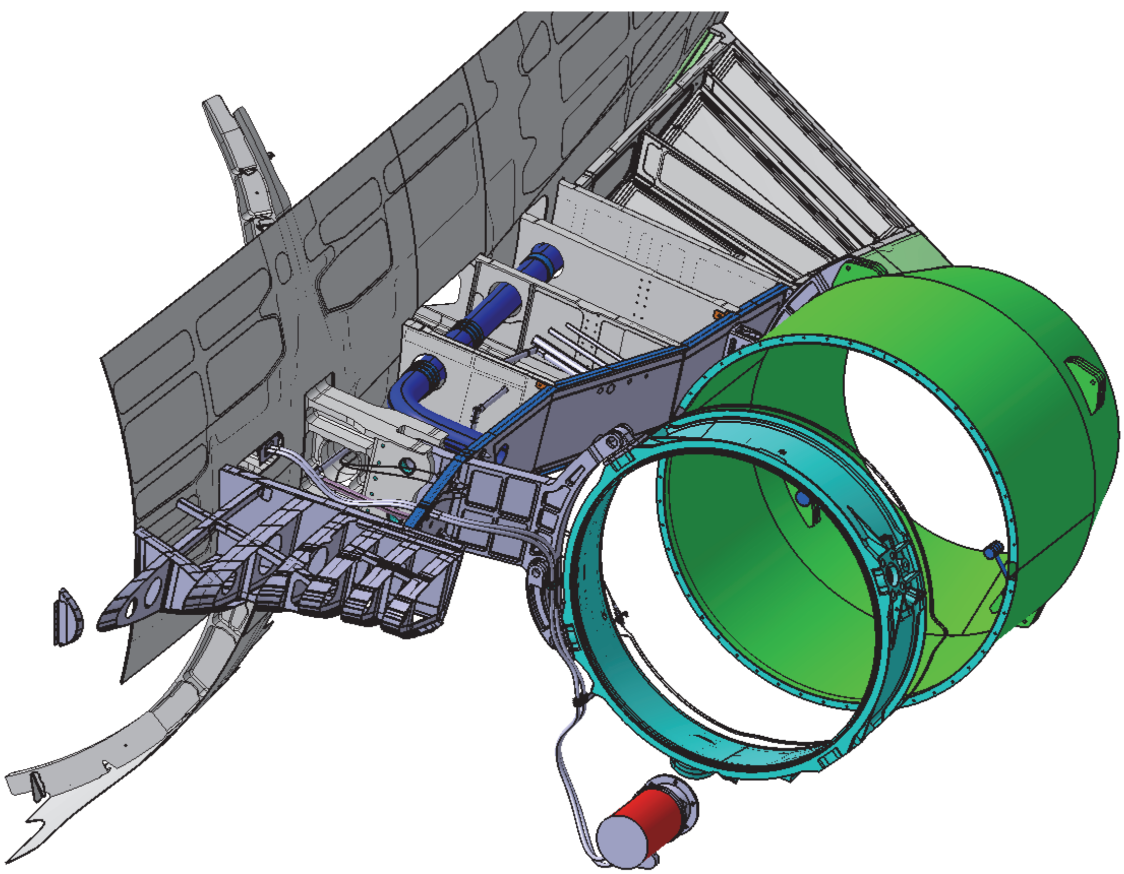


Figure 6.18: Improved firewall driven by explorations of the design bandwidth

It should be noted that SBCE as simualed with the CCS approach in a knowledge-based environment is a practice that itself is meant to generate, structure and leverage codified knowledge throughout its implementation. Knowledge is understood here in Konda et al. sense of "useful and workable abstractions of reality" for progressing *vertical* and *horizontal* shared memory (Konda et al., 1992). Indeed, a methodology that supports a culture of continuous creation and appropriate structuring of organisational knowledge is the basis of the superior development system advocated herein. Knowledge management aspects not adressed during the simulation include techniques for generating trade-off curves from prototyping and testing as well as practices for supporting knowledge transfer within an organisation i.e. conversion between *tacit* and *explicit* knowledge (Lindlöf, Söderberg, & Persson, 2013).

CHAPTER 7 CONCLUSION AND RECOMMENDATIONS

The work reported in this thesis is the result of seven years of participatory action research in the field of lean product development in aerospace engineering. This research is motivated by the necessity to develop understanding and support for practical implementations of lean product development and especially set-based design in industry. Such necessity is justified by 21^{st} century compelling socioeconomic factors that demand robust, resilient, responsive, flexible, innovative, adaptable and lean product development processes in order for companies to stay competitive in rapidly changing markets.

The main purpose of the research was to identify and develop the essential SBCE and LPD aspects, characteristics, features and catalysts as they relate to aerospace large-scale industrial product development in order to form a holistic model that can support practical implementations of LPD in industry from a product lifecycle perspective.

A comprehensive review of lean, PD, and LPD literature was first presented by discussing the concepts, theoretical grounds, practical implications and advances in the fields. Recent studies on lean PD in aerospace industry showed that the maturity of lean PD implementation in the industry is low, no more than at introductory level and it has not been possible so far to find a company that coherently combines the LPD enablers into a whole to improve its PD process in a lean way (Al-Ashaab et al., 2016; Beauregard et al., 2014; McManus et al., 2005; Rebentisch, 2008). The comprehensive review also showed that LPD research has focused on the principles and concepts underlying LPD i.e. what should be done, the tools and techniques to implement the approach, rather than converging to a mature theory/model (conceptual focus and theory-building) and the methodologies for the implementation, tool integration, coordination strategies, performance measures and causality effect assessments (Hoppmann et al., 2011; León & Farris, 2011). It was also observed that the models and methodologies should show compatibility with conventional PD assets and deployed technology in order to avoid disruption but rather stay within the bandwidth of long-term investments while positively balancing the burden of their implementation (Khan, 2012; León & Farris, 2011). Set-based Engineering, set-based design or SBCE (the practice of set-based design) emerged from this first step review as a strong component of LPD with all authors describing it as the core enabler of LPD. For instance, Ward et al. (1995) mention that "companies adopting concurrent engineering through cross-functional teams and structured development process that focus on designing the right product in the concept stage will inevitably move in the direction of set-based concurrent engineering".

A systematic review of SBCE was therefore carried for the above reasons, but also because it is simply the main focus of the present research. This systematic review followed an evidence-based procedure (NHS, 2001; Tranfield et al., 2003) to analyse the existing SBCE literature by using a newly devised dual analysis framework. The review question, according to the evidence-based systematic review procedure requirements, was to discover and analyse SBCE literature characteristics, enablers and catalysts for proposing/developing holistic models and methodologies intended to support the transition to SBCE from the current PD practice, conventional tools and assets. The new SBCE analysis framework was therefore designed in this thesis for the purpose of assessing the research paradigms and methods used in SBCE research to generate new knowledge about SBCE on one side and, on the other side, the coverage of the engineering design process available in each discovered approach when it comes to proposing/developing holistic models and methodologies intended to support the transition to SBCE from the current practice. Data collection for the systematic review resulted in **154** relevant research publications, which were then subdivided into five categories with the last pertaining specifically to the development of SBCE theories, models and methodologies for its practical implementation. While mixed quantitative and qualitative methods were used to analyse the five categories in order to assess the relevance, importance, breadth and depth of the SBCE research topics from the overall research community perspective, the last category (Cat-5), which pertains to this thesis work, was thoroughly examined through the dual analysis framework. This analysis culminated in a synthesis which followed a succession of epochs centered upon the formulation of the “second Toyota paradox” by Ward, Liker, Cristiano and Sobek (1995). It was evidenced from the synthesis that:

- Research is required to extend the application of SBCE theories and principles beyond the conceptual design stage, especially implications for detailed design, prototyping, testing and the rest of the product lifecycle;

- There is a lack of holistic model that can support the cross-domain communication, overlapping, narrowing, and refinement of sets and, furthermore, enable the iterative institutional learning capability which is core to SBCE and lean PD;
- Product structuring, configurability and variability are recognized as practical SBCE enablers but they remain scarce within the SBCE literature. Their ability to enable SBCE is not explored from a holistic PD, lifecycle perspective and by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework i.e. PDM/PLM;
- Although the literature regularly stipulates that extensive prototyping and testing is key to SBCE in order to foster the Knowledge-Based environment, institutional learning capability and to inform the decision-making process, prototyping (virtual and physical) and testing (incl. simulations) frameworks and activities are rarely addressed within the SBCE literature;
- The effects of major SBCE enablers e.g. product structuring, configurability, prototyping, set-based selection process etc. on the development process performance are rarely studied, whether by experimenting alternative hypothesis or disproving null hypothesis.

These research opportunities led to the formulation of research questions as follows:

RQ1. What aspects, characteristics and features of the aerospace industrial product development are catalysts of a potential transition to SBCE and LPD?

RQ2. What is an appropriate approach for various domains of expertise within the aerospace industrial product development to exchange on the basis of alternative design solutions and furthermore, narrow down to an optimal design by following a set-based convergence process?

RQ3. Does a holistic model exist or can it be developed to support the transition from traditional product development to SBCE and LPD in a product lifecycle perspective?

The research was designed to appropriately answer the type of inquiries by substantiating and validating hypotheses while refuting selected null hypothesis. To summarize, based upon the research objectives, inquiries and the involvement of the author in a community seeking for change towards lean product lifecycle management, the research design resulted in a mixed quantitative-qualitative participatory action research by using socio-dynamics data collection/analysis methods from ethnomethodology and an overarching methodology (DRM) by Blessing and Chakrabarti (2009). This overarching methodological sequence was primarily used for planning and executing the design research project while ensuring that focus is placed on achieving substantial progress with regards to understanding and implementation of SBCE and LPD as Design practices. As such, the research clarification phase mainly consisted in the literature review and methodology which, for the first, readily resulted in two contributions from this research i.e. **(1)** the proposal of a new SBCE dual analysis framework combined with an evidence-based systematic review methodology and; **(2)** the advancement of theoretical and practical understanding of LPD and SBCE from the larger to the most significant aspects. Drawing upon findings from the literature review, Descriptive Study I followed by studying identified major influences both from the literature and practitioners standpoint. The study addressed the lack of inquiries into the dynamics of cross-collaboration during aerospace product development, the reality of digital product information, product modelling, configurability, prototyping (virtual and physical) and testing (incl. simulations) as they pertain to practical implementations of SBCE and LPD. A configuration methodology for non-isomorphic hierarchies and complementary information structures was proposed and demonstrated to enable the parallel exploration of multiple prototypes by synchronising design, development, simulation, manufacturing and testing streams while securing all gathered knowledge. This was found to promote institutional learning capabilities through structured set-based prototyping, to allow for contextual 3D visualisations including as-built DMU and to support effective change propagation in heterogeneous domains. Contributions from Descriptive Study I include: **(3)** the advancement of theoretical and practical understanding of product models and product structure progression requirements for lean product lifecycle management and; **(4)** the proposal of a new methodology, including new *as-tested* structure to support cross-collaboration during prototyping and testing in lifecycle management contexts. The complementary information structures approach expounded upon in Descriptive Study I was then developed into a new multi-domain Configurable Complementary Structures (CCS) model by transposing identified SBCE relevant models of the design process into a representational formalism for product modelling and generic product structuring in lifecycle management contexts; So as to enable practical transitions from the current practice to SBCE. This mainly consisted in DRM Prescriptive Study. Figure 7.1 illustrates configuration tracking granularity within the CCS approach. Each possible design alternative can be maintained at the conceptual level as well as throughout its next lifecycle stages evolution. This is done by leveraging CCS underlying combination of architectural option (AO) effectivities (**rs**, **lf, gbom** parameter effectivities) in functional and technological domains as well as change evolution effectivities (**dp** date, unit or version effectivities) after the AO is instantiated in the physical domain.

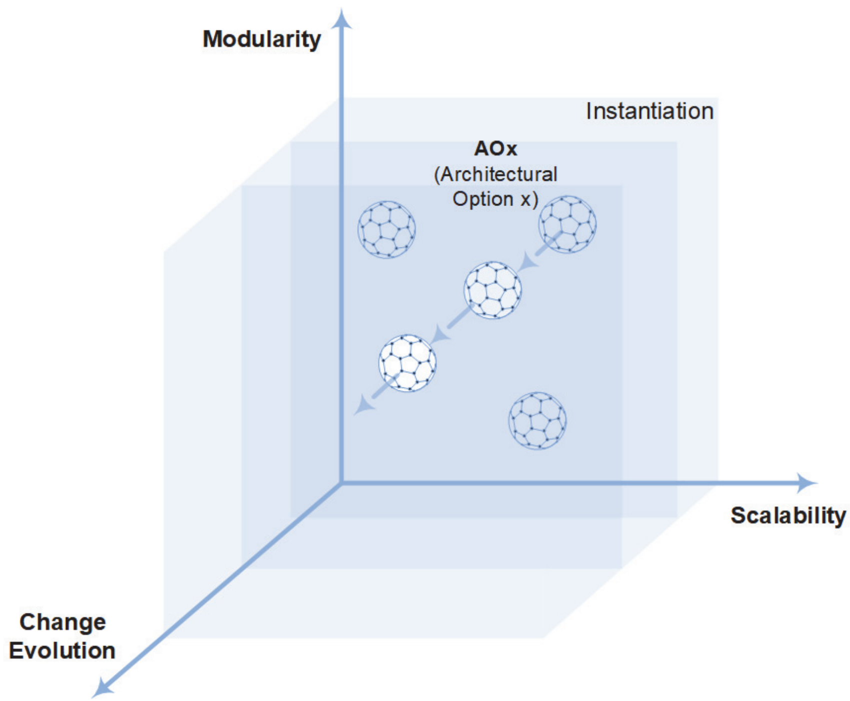


Figure 7.1: CCS effectivity-based variability and change evolution coverage

It is argued that the multi-domain product modelling, variability and configurability approach devised herein together hold the potential to support explorations of a product platform design space by allowing various disciplines involved in the product lifecycle to consider sets of distinct alternatives concurrently so as to appropriately inform a set-based design convergence process. This is in support to the implementation of the first set-based design fundamental principle as stipulated by Gosh and Seering (2014), i.e. principle A. It is also argued that the approach allows for the preservation of conceptual solution sets until variants are instantiated in the physical domain and data is cross-functionally collected to inform the decision-making process. This is in support to the implementation of the remaining set-based design fundamental principle i.e. principle B. The multi-domain approach can effectively support implementations of these fundamental principles in the sense that, by using the proposed framework and, as noted by Gosh and Seering (2014), the principles can manifest themselves in all phases of the design process, not limited to the conceptual phase or the interface with detailed design phases.

To ensure full coverage of the product lifecycle, a new *existential* domain was introduced in the CCS multi-domain approach alongside the functional, technological and physical domains. This was inferred as such in order to address the lack of product modelling constructs and methodology when it comes to service or as-tested configurations, hardware testing transactions and prototype information tracking on the basis of serialized components. The new *existential* domain represents a fifth contribution **(5)** from this research alongside the overall proposed CCS model for practical implementations of SBCE in lifecycle management contexts **(6)**. Continuing on DRM Prescriptive Study, the CCS model, with its variability and multi-domain configurability features, was complemented with 3D-based overlapping methods and set-based elimination tools in order to fully substantiate **H1$_1$** and **H2$_1$** recalled below:

H1$_1$: A product structuring model that supports concurrent engineering on one hand and, the configurable virtual product synchronized with prototyping as-tested structures on the other hand, can provide effective means to enable an enterprise level SBCE that spans the product lifecycle;

H2$_1$: Virtual prototyping tuned by physical prototyping and, combined with a set-based selection process/matrix, can form an appropriate basis for overlapping and narrowing independent solution sets;

The CCS model and extended methods were subsequently extrapolated to the Learning Value Streams (LVS) model by encompassing the core LPD enablers identified during the literature review as well as virtual product management practices studied during Descriptive Study I and beyond. The so-called LVS model, presented in Fig. 7.2, combines all studied essential enablers into a cohesive whole and, therefore, substantiates **H3$_1$** which is recalled below. The LVS model, as devised, constitutes the seventh and last contribution from this research **(7)**.

H3$_1$: The transition from the aerospace traditional PD to LPD in a product lifecycle perspective and, by using a continuum of tools and methodology as they pertain to large-scale industry conventional PD supporting framework, can be achieved through the implementation of a holistic model.

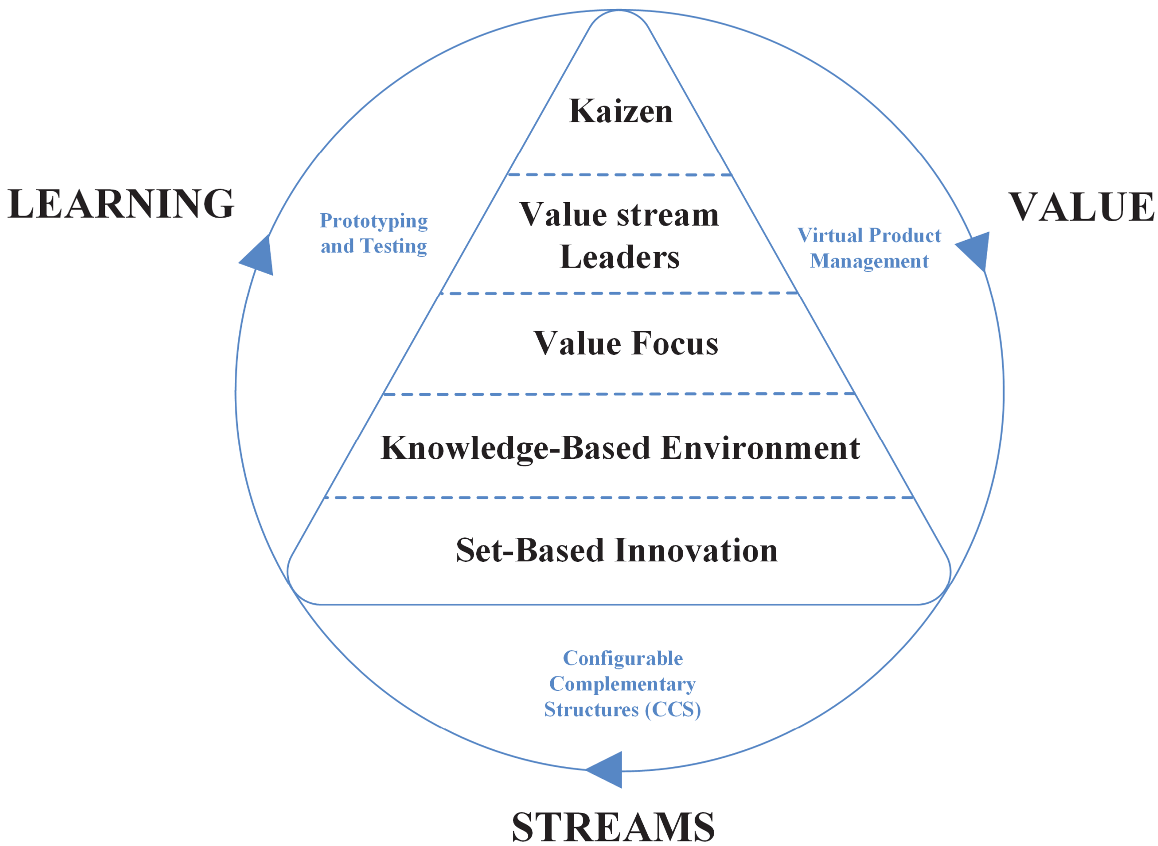


Figure 7.2: A model for practical implementations of LPD in large-scale industrial contexts

It was possible to emulate the proposed CCS model (validation of $\mathbf{H1_1}$ and $\mathbf{H2_1}$) in the context of a commercially available and widespread PLM platform. The simulation was performed in four months by a small team of experienced engineers and novice designers who leveraged typical off the shelf constructs and configurator engine of the conventional PLM system in use at the company. Such setting replicated the realistic design context prescribed by DRM for Descriptive Study II. The study consisted in a pilot simulation of the proposed methodology through the exploration of three design alternatives of an aircraft pylon. The three architectural options primarily referred to a range of available options for the design of the engine firewall.

Two limitations were found during the simulation. First is the known lack of proper configuration methodology for as-tested structures as already observed and resolved in Descriptive Study I through the design and deployment of new PLM extensions. The other limitation is the inability of the system, as-simulated, to automatically convert the technological domain explicit structure (logical structure) into the physical domain (explicit BOM) so that the same AOs can be simultaneously filtered in the synchronized explicit BOM without having to duplicate the configuration effort. No customization was done to reflect CCS intended domain effectivities synchronization due to the resources and time allocated to the simulation. This should be done in future validation to better reflect CCS model distinctive intent as well as overall resulting benefits. For the time being, the CCS approach was found during the simulation to enable a setting that promotes innovation. The team appreciated “getting into this mindset” of combining all possible options into a range of available design alternatives in order to carefully consider each and document them concurrently. All participants recognized that the approach, as deployed, was effective for discovering new solutions by pushing the team to explore further and only commit once they have enough data to conclude about the weakness of a design. Such exploration opens the door to the discovery of unknown properties of a design, then the discovery of new solutions space by progressively combining options, which ultimately leads to innovation. The simulation, indeed, validated implementation of SBCE in the context of a large-scale industry conventional PD supporting framework. This by demonstrating how multiple disciplines may overlap their own solution options with other discipline options by communicating on the basis of a range of available alternatives, which alternatives are structured within the environment in conformance with the CCS multi-domain, cross-lifecycle-phase approach and reusable knowledge underpinnings.

As far as validation is concerned, the primarily qualitative research was conducted and reported as formalised by Golafshani (2003), which means by ensuring precision, consistency, credibility, confirmability, applicability and transferability in order to achieve reliability and validity by eliminating bias and increasing the researcher’s trustworthiness in its proposals. Then triangulation was perceived to be the validity procedure that relies on multiple methods of data collection and data analysis, leading to a more valid, reliable convergence to the themes, categories and interpretations formed in the study (Creswell & Miller, 2000). A manifestation of this can be found in the triangulation that resulted from performing pilot simulations (Descriptive Study I and II) in two separate commercially available and major aerospace industry PLM platforms in order to independently assess the proposed methodologies and infer PLM platform-neutral recommendations. The approach followed for the literature review and, especially the design and conducting of an evidence-based systematic review of SBCE, also manifests reliability and validity in this research.

From a design research standpoint, the use of success criteria for action research in design, as initially advocated in DRM, has been criticized because success criteria are believed to focus the study on (sometimes invalid, unreliable) metrics, disregarding unanticipated influences by simply paying too much attention to the so-thought measurable premises (Eckert et al., 2004; Reich, 1995). Success criteria are believed to be "of limited utility in evaluating the success of introducing new tools, methods and procedures into design processes in industry" (Eckert et al., 2004). According to the authors, the most useful criteria for success is the advancement of knowledge i.e. understanding design, and the perception of value in new procedures and methods by practitioners in industry. These criteria were retained and met in the current research mainly through the seven major contributions summarized above, the outcomes and practitioners' perception from the two pilot simulation and, more generally, the author's own experience in industry as reported throughout the dissertation. Another noticeable is the validation of the methods and contributions by academic experts in the field based upon presentation on August 21st, 2017 at the PhD forum of the 21st International Conference on Engineering Design (ICED'17) in Vancouver, Canada.

This thesis work provides substantial contribution to understanding of LPD and SBCE and furthermore, entails valuable proposal for the practice of LPD and SBCE in industry through the CCS model and the construction of the LVS model.

It was not possible to perform complete validation of the LVS model (**$H3_1$**) as a whole because it requires real life deployment or real life pilot projects with significant resources and monitoring for a potentially extended period of time. It is therefore recommended to pursue such validation in future work. Future research should also clarify supplier integration during implementation of the LVS model as supplier/partner involvement early in the design process was also identified as a key LPD characteristic of the *lean enterprise* (Ghosh & Seering, 2014;

Hoppmann et al., 2011; León & Farris, 2011; Liker et al., 1996; Womack et al., 1991). Although it is argued herein that suppliers and partners can readily be involved in an environment implementing CCS, just like any other internal participant to the enabled set-based concurrent engineering context, knowledge management and value stream leadership should be further clarified in such context, especially with respect to design responsibility, intellectual property and export control constraints. Nevertheless, SBCE as simualed with the CCS approach in a knowledge-based environment is a practice that itself is meant to generate, structure and leverage codified knowledge throughout its implementation. Knowledge is understood here in Konda et al. sense of “useful and workable abstractions of reality” for progressing *vertical* and *horizontal* shared memory (Konda et al., 1992). Indeed, a methodology that supports a culture of continuous creation and appropriate structuring of organisational knowledge is the basis of the superior development system advocated herein. Knowledge management aspects not adressed in the thesis include the science of generating trade-off curves from prototyping and testing as well as practices for supporting knowledge transfer within an organisation i.e. conversion between *tacit* and *explicit* knowledge (Lindlöf et al., 2013). This should be adressed in future researh as it relates to the proposed LVS model.

From a deployment standpoint, aerospace companies may naturally use several set-based techniques but the unusual length of their aircraft development phase, the complex organisation of their supply chain, and the difficulty to modularize aircraft functionalities may remain major stumbling blocks towards proper SBCE implementation. SBCE, LPPD and lean in general are primarily strategic endeavours with a strong desire at every single level of a company to make the underlying philosophies a part of their DNA. This can only be achieved by people’s willingness to change. People’s willingness to continuously seek for perfection.

REFERENCES

Al-Ashaab, A., Golob, M., Attia, U. M., Khan, M., Parsons, J., Andino, A., Perez, A., Guzman, P., Onecha, A., & Kesavamoorthy, S. (2013). The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry. *Concurrent Engineering, 21*(4), 268-285.

Al-Ashaab, A., Golob, M., Urrutia, U. A., Gourdin, M., Petritsch, C., Summers, M., & El-Nounu, A. (2016). Development and application of lean product development performance measurement tool. *International Journal of Computer Integrated Manufacturing, 29*(3), 342-354.

Alberts, D. S., & Hayes, R. E. (2003). *Power to the edge: Command... control... in the information age*. Washington DC Office of the assistant secretary of defense, Command and Control Research Program (CCRP), Defense Technical Information Center (DTIC).

Altshuller, G. (1984). *Creativity as an Exact Science*. New York, NY: Gordon & Breach.

Anderl, R., Malle, B., & Schmidt, M. (1992). *Concurrent engineering based on a product data model*. Paper presented at the Proceedings of CALS EUROPE '92, Paris, France.

Andreasen, M. M. (1991). *The theory of domains*. Paper presented at the Proceedings of EDC Workshop on understanding function and function-to-form evolution, University of Cambridge, Cambridge, UK.

Andreasen, M. M. (1992). *Designing on a "Designer's Workbench"(DWB)*. Paper presented at the Proceedings of the 9th WDK Workshop, Rigi, Switzerland.

Andreasen, M. M. (1998). *Reduction of the complexity of product modelling by modularisation*. Paper presented at the Conference on product models, Produktmodeller'98, Linköping, Sweden.

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

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

Antonsson, E. K., & Wood, K. L. (1989). Computations with imprecise parameters in engineering design: background and theory. *ASME Journal of Mechanisms, Transmissions and Automation in Design, 111*(4), 616-625.

Araci, Z. C., Al-Ashaab, A., & Maksimovic, M. (2015). *A Process of Generating Trade-off Curves to Enable Set-Based Concurrent Engineering*. Paper presented at the Proceedings of the 16th European Conference on Knowledge Management: ECKM 2015, University of Udine, Italy

Araci, Z. C., Al-Ashaab, A., & Maksimovic, M. (2016). Knowledge Creation and Visualisation by Using Trade-off Curves to Enable Set-based Concurrent Engineering. *Electronic Journal of Knowledge Management, 14*(1), 75-88.

Asimow, M. (1962). *Introduction to design*: Prentice-Hall Englewood Cliffs, NJ.

Augustine, M., Yadav, O. P., Jain, R., & Rathore, A. P. S. (2010). Concept convergence process: A framework for improving product concepts. *Computers & Industrial Engineering, 59*(3), 367-377.

Avigad, G., & Moshaiov, A. (2009). Set-based concept selection in multi-objective problems: optimality versus variability approach. *Journal of Engineering Design, 20*(3), 217-242.

Avigad, G., & Moshaiov, A. (2010). Set-based concept selection in multi-objective problems involving delayed decisions. *Journal of Engineering Design, 21*(6), 619-646.

Baines, T., Lightfoot, H., Williams, G. M., & Greenough, R. (2006). State-of-the-art in lean design engineering: A literature review on white collar lean. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 220*(9), 1538-1547.

Baxter, M. (1995). *Product design: a practical guide to systematic methods of new product development*. New York: Chapman & Hall.

Baxter, P., & Jack, S. (2008). Qualitative case study methodology: Study design and implementation for novice researchers. *The qualitative report, 13*(4), 544-559.

Beauregard, Y., Bhuiyan, N., & Thomson, V. (2014). Lean engineering performance analysis. *International Journal of Product Development, 19*(5-6), 366-387.

Becker, J. M. J., & Wits, W. W. (2015). *Enabling lean design through computer aided synthesis: The injection moulding cooling case*. Paper presented at the 4th CIRP Global Web Conference, Cranfield, UK.

Berglund, F., & Claesson, A. (2005). *Utilising the concept of a design's bandwidth to achieve product platform effectiveness*. Paper presented at the Proceedings of the 15th International Conference on Engineering Design, ICED 05, Melbourne, Australia.

Bergstrom, C. (2007). Eigenfactor: Measuring the value and prestige of scholarly journals. *C&RL News, 68*(5), 314-316.

Bernstein, J. (1998). *Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices.* (Master Thesis, Massachusetts Institute of Technology, Boston, Massachusetts).

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

Blessing, L. T. M., & Chakrabarti, A. (2009). *DRM, A Design Research Methodology*. London, UK: Springer-Verlag.

Blomkvist, J., & Holmlid, S. (2012). *Service prototyping according to service design practitioners*. Paper presented at the Proceedings of ServDes. 2010; Exchanging Knowledge, Linköping; Sweden.

Boehm, B., & Hansen, W. J. (2000). *Spiral development: Experience, principles, and refinements*. Carnegie Mellon University: Defense Technical Information Center.

Boehm, B., & Turner, R. (2004). *Balancing agility and discipline: Evaluating and integrating agile and plan-driven methods*. Paper presented at the Proceedings of the 26th International Conference on Software Engineering, ICSE'04, Edinburgh, Scotland, UK.

Bourke, V. J. (1962). Rationalism. *Dictionary of philosophy. Totowa, NJ: Littlefield Adams, and Company*.

Brière-Côté, A., Rivest, L., & Desrochers, A. (2010). Adaptive generic product structure modelling for design reuse in engineer-to-order products. *Computers in industry, 61*(1), 53-65.

Brissaud, D., & Tichkiewitch, S. (2001). Product models for life-cycle. *CIRP Annals - Manufacturing Technology, 50*(1), 105-108.

Browning, T. R. (2000). *Value-based product development: refocusing lean*. Paper presented at the Proceedings of the 2000 IEEE Engineering Management Society, EMS - 2000, Albuquerque, New Mexico.

Browning, T. R. (2003). On customer value and improvement in product development processes. *Systems Engineering, 6*(1), 49-61.

Browning, T. R., & Ramasesh, R. V. (2007). A Survey of Activity Network-Based Process Models for Managing Product Development Projects. *Production and operations management, 16*(2), 217-240.

Bucciarelli, L. L. (1994). *Designing engineers*: MIT press.

Button, G. (2000). The ethnographic tradition and design. *Design studies, 21*(4), 319-332.

Buur, J., & Andreasen, M. M. (1989). Design models in mechatronic product development. *Design studies, 10*(3), 155-162.

Camburn, B. A., Arlitt, R., Perez, K. B., Anderson, D., & Kun, P. (2017). *Design Prototyping of Systems*. Paper presented at the Proceedings the 21st International Conference on Engineering Design, ICED 2017, Vancouver, BC, Canada.

Camburn, B. A., Dunlap, B., Gurjar, T., Hamon, C., Green, M., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2015a). A Systematic Method for Design Prototyping. *Journal of Mechanical Design, 137*(8), 08110201-08110212.

Camburn, B. A., Dunlap, B., Kuhr, R., Viswanathan, V. K., Linsey, J., Jensen, D. D., Crawford, R., Otto, K., & Wood, K. L. (2013). *Methods for prototyping strategies in conceptual* *phases of design: Framework and Experimental Assessment*. Paper presented at the Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2013, Portland, Oregon, USA.

Camburn, B. A., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2015b). *Evaluation of a Strategic Method to Improve Prototype Performance with Reduced Cost and Fabrication Time*. Paper presented at the Proceedings of the 20th International Conference on Engineering Design, ICED 15, Milan, Italy.

Canbaz, B., Yannou, B., & Yvars, P.-A. (2011). *A New Framework for Collaborative Set-Based Design: Application to the Design Problem of a Hollow Cylindrical Cantilever Beam*. Paper presented at the Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2011, Washington, DC, USA.

Canbaz, B., Yannou, B., & Yvars, P.-A. (2014). Improving process performance of distributed set-based design systems by controlling wellbeing indicators of design actors. *Journal of Mechanical Design, Transactions of the ASME, 136*(2), 021005.

Canuto da Silva, G., & Kaminski, P. C. (2016). Selection of virtual and physical prototypes in the product development process. *The International Journal of Advanced Manufacturing Technology, 84*(5), 1513-1530.

Carleton, T., & Cockayne, W. (2009). *The power of prototypes in foresight engineering*. Paper presented at the Proceedings of the 17th International Conference on Engineering Design, ICED'09, Stanford, CA, USA.

Chen, P. P.-S. (1976). The entity-relationship model—toward a unified view of data. *ACM Transactions on Database Systems (TODS), 1*(1), 9-36.

Cho, Y. S., Lee, S. I., & Bae, J. S. (2014). Reinforcement placement in a concrete slab object using structural building information modeling. *Computer-Aided Civil and Infrastructure Engineering, 29*(1), 47-59.

Christie, E. J., Jensen, D. D., Buckley, R. T., Menefee, D. A., Ziegler, K. K., Wood, K. L., & Crawford, R. H. (2012). *Prototyping strategies: literature review and identification of critical variables*. Paper presented at the Proceedings of the 2012 American Society for Engineering Education (ASEE) Annual Conference & Exposition, Design Tools and Methodology II, San Antonio, TX, USA.

Claesson, A. (2006). *A configurable component framework supporting platform-based product development.* (PhD Thesis, Chalmers University of Technology, Göteborg, Sweden).

Claesson, A., & Johannesson, H. (2006). *Integrated and Configurable Product and Manufacturing Models*. Paper presented at the Proceedings of the 9th International Design Conference, DESIGN 2006, Dubrovnik, Croatia.

Clark, K. B., Chew, W. B., Fujimoto, T., Meyer, J., & Scherer, F. (1987). Product development in the world auto industry. *Brookings Papers on Economic Activity, 1987*(3), 729-781.

Clark, K. B., & Fujimoto, T. (1991). *Product development performance : Strategy, organization, and management in the world auto industry.* Boston, Massachusetts: Harvard Business School Press.

Clarkson, P. (2006). An Optimal Design Process for an Adequate Product? In R. Rohatyński & Z. Góra (Eds.), *Design Methods for Practice* (pp. 21-26).

Colton, J. S., & Pun, R. C. (1994). Information frameworks for conceptual engineering design. *Engineering with computers, 10*(1), 22-32.

Cook, D. J., Greengold, N. L., Ellrodt, A. G., & Weingarten, S. R. (1997a). The relation between systematic reviews and practice guidelines. *Annals of internal medicine, 127*(3), 210-216.

Cook, D. J., Mulrow, C. D., & Haynes, R. B. (1997b). Systematic reviews: synthesis of best evidence for clinical decisions. *Annals of internal medicine, 126*(5), 376-380.

Cooper, H. M. (1998). *Synthesizing research: A guide for literature reviews* (Vol. 2): Sage.

Cooper, R. G. (1994). Third-generation new product processes. *Journal of product innovation management, 11*(1), 3-14.

Coyle, J. M., & Paul, D. (1997). *Virtual Product Definition – The Key to Affordable and Supportable Products.* Paper presented at the Proceedings of the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", Palaiseau, France.

Creswell, J. W., Hanson, W. E., Clark Plano, V. L., & Morales, A. (2007). Qualitative research designs: Selection and implementation. *The counseling psychologist, 35*(2), 236-264.

Creswell, J. W., & Miller, D. L. (2000). Determining validity in qualitative inquiry. *Theory into practice, 39*(3), 124-130.

Crnkovic, I., Asklund, U., & Dahlqvist, A. P. (2003). *Implementing and integrating product data management and software configuration management*: Artech House.

Cross, N. (1984). *Developments in design methodology*: John Wiley & Sons.

Cross, N. (1989). *Engineering design methods* (Vol. 4): Wiley New York.

de Souza, V. M., & Borsato, M. (2016). Combining Stage-Gate™ model using Set-Based concurrent engineering and sustainable end-of-life principles in a product development assessment tool. *Journal of Cleaner Production, 112*(4), 3222-3231.

Deming, W. E. (2000). *The new economics: for industry, government, education*: MIT press.

Dolezal, W. R. (2008). *Success Factors for Digital Mock-ups (DMU) in complex Aerospace Product Development.* (Technische Universität München, Genehmigten Dissertation, Munich, Germany.).

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

Dunlap, B. U., Hammon, C., Camburn, B. A., Crawford, R., Jensen, D., Green, M. G., Otto, K., & Wood, K. L. (2014). *Heuristics-based prototyping strategy formation: development and testing of a new prototyping planning tool*. Paper presented at the Proceedings of the ASME 2014 International Mechanical Engineering Congress & Exposition, IMECE2014, Montreal, Quebec, Canada.

Durmuşoğlu, S. S., & Barczak, G. (2011). The use of information technology tools in new product development phases: Analysis of effects on new product innovativeness, quality, and market performance. *Industrial Marketing Management, 40*(2), 321-330.

Eckert, C., Clarkson, P. J., & Stacey, M. (2004). *The lure of the measurable in design research*. Paper presented at the Proceedings of the 8th International Design Conference, DESIGN 2004, Dubrovnik, Croatia.

Eckert, C., Stacey, M., & Clarkson, P. J. (2003). *The spiral of applied research: A methodological view on integrated design research*. Paper presented at the Proceedings of the 14th International Conference on Engineering Design, ICED'03, Stockholm, Sweden.

EIA-649-B. (2011). *Configuration Management Standard*: SAE Publications.

Eigner, M., & Fehrenz, A. (2011). *Managing the product configuration throughout the lifecycle*. Paper presented at the Proceedings of the 8th International Conference on Product Lifecycle Management, Eindhoven, The Netherlands.

Elhariri Essamlali, M. T., Sekhari, A., & Bouras, A. (2017). Product lifecycle management solution for collaborative development of Wearable Meta-Products using set-based concurrent engineering. *Concurrent Engineering, 25*(1), 41-52.

ElMaraghy, W. H., & Jack, H. (1993). *Facilitating Rapid Product Realization with a High-Level CAPP System*. Paper presented at the Proceedings of the IFIP TC5/WG5. 3 Conference on Towards World Class Manufacturing 1993, Litchfield Park, Arizona, USA.

Enge-Rosenblatt, O., Clauß, C., Schneider, A., & Schneider, P. (2011). *Functional Digital Mock-up and the Functional Mock-up Interface-Two Complementary Approaches for a Comprehensive Investigation of Heterogeneous Systems*. Paper presented at the Proceedings of the 8th International Modelica Conference, Technical Univeristy, Dresden, Germany.

Erens, F. (1996). *The synthesis of variety: developing product families.* (PhD Thesis, Technische Universiteit Eindhoven, The Netherlands).

Erens, F., & Verhulst, K. (1997). Architectures for product families. *Computers in industry, 33*(2-3), 165-178.

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

Evans, J. H. (1959). Basic design concepts. *Naval Engineers Journal, 71*(4), 671-678.

Eversheim, W., & Schulten, I. (1999). Optimal degree of parallelism and integration in design and process planning. In H. Kals & F. Van Houten (Eds.), *In: Integration of process knowledge into design support systems* (pp. 118-128). Dordrecht, The Netherlands: Kluwer Academic Publishers.

FAA. (2016). *Part 25-Airworthiness standards: Transport category airplanes, Subpart E - Powerplant, Subgrp - Powerplant Fire Protection, Section § 25.1191 - Firewalls.* USA: Federal Aviation Administration, Department of transportation.

Fersht, A. (2009). The most influential journals: Impact Factor and Eigenfactor. *Proceedings of the National Academy Sciences, 106*(17), 6883–6884.

Finch, W. W., & Ward, A. C. (1997). *A set-based system for eliminating infeasible designs in engineering problems dominated by uncertainty*. Paper presented at the Proceedings of the 1997 ASME Design Engineering Technical Conferences, DETC97, Sacramento, CA, USA.

Fink, A. (2005). *Conducting research literature reviews: from the Internet to paper*: Sage.

Ford, D. N., & Sobek, D. K. (2005). Adapting real options to new product development by modeling the second Toyota paradox. *IEEE Transactions on Engineering Management, 52*(2), 175-185.

Forsberg, K., & Mooz, H. (1999). *System Engineering for Faster, Cheaper, Better*. Paper presented at the Proceedings of the 9th annual international symposium (INCOSE), Brighton, England.

Fortin, C., & Huet, G. (2007). Manufacturing Process Management: iterative synchronisation of engineering data with manufacturing realities. *Int. J. Product Development, 4*(3), 280-295.

Fortin, C., Huet, G., Sanschagrin, B., & Gagné, S. (2006). The CAMAQ project: a virtual immersion in aerospace industry practices. *World Transactions on Engineering and Technology Education, 5*(2), 287-290.

Fortin, C., Toche, B., McSorley, G., & Huet, G. (2010). *Supporting Product Development Value Streams through Manufacturing Process Management*. Paper presented at the Proceedings of the 1st International Conference on Modelling and Management of Engineering Processes, MMEP'10, Cambridge, UK.

Fukuda, S., Lulic, Z., & Stjepandic, J. (2013). *FDMU-Functional Spatial Experience Beyond DMU?* Paper presented at the Proceedings of the 20th ISPE International Conference on Concurrent Engineering, Melbourne, Australia.

Garbade, R., & Dolezal, W. (2007). *DMU@ Airbus—Evolution of the Digital Mock-up (DMU) at Airbus to the Centre of Aircraft Development*. Paper presented at the Proceedings of the 17th CIRP Design Conference. User Keynote, the future of product development, Cranfield, UK.

Gausemeier, J., Berssenbrügge, J., Grafe, M., Kahl, S., & Wassmann, H. (2011). *Design and VR/AR-based testing of advanced mechatronic systems*. Paper presented at the Proceedings of the 2nd Sino-German Workshop. Virtual Reality & Augmented Reality in Industry., Shanghai, China.

Gerber, E. (2009). *Prototyping: Facing uncertainty through small wins*. Paper presented at the Proceedings of the 17th International Conference on Engineering Design, ICED'09, Stanford, CA, USA.

Ghosh, S., & Seering, W. (2014). *Set-Based Thinking in the Engineering Design Community and Beyond*. Paper presented at the Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2014, Buffalo, NY, USA.

Giachetti, R. E. (1997). Manufacturing Process and Material Selection During Conceptual Design. *Industrial Engineering Research–Conference Proceedings, 47250* 772-777.

Glaessgen, E. H., & Stargel, D. (2012). *The Digital Twin paradigm for future NASA and US Air Force vehicles*. Paper presented at the Proceedings of the 53rd Struct. Dyn. Mater. Conf., Special Session: Digital Twin, Honolulu, HI, US.

Glaser, B. G. (1978). *Theoretical sensitivity: Advances in the methodology of grounded theory*: Sociology Pr.

Golafshani, N. (2003). Understanding reliability and validity in qualitative research. *The qualitative report, 8*(4), 597-606.

Greenhalgh, T. (1997). Papers that summarise other papers (systematic reviews and meta-analyses). *BMJ: British Medical Journal, 315*(7109), 672.

Gutek, G. L. (2013). *Philosophical, ideological, and theoretical perspectives on education*: Pearson Higher Ed.

Häggman, A., Honda, T., & Yang, M. C. (2013). *The influence of timing in exploratory prototyping and other activities in design projects*. Paper presented at the Proceedings of the ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2013, Portland, OR, USA.

Hammon, C., Green, M., Dunlap, B., Camburn, B., Crawford, R., & Jensen, D. (2014). *Virtual or physical prototypes? Development and testing of a prototyping planning tool*. Paper presented at the Proceedings of the121st ASEE Annual Conference & Exposition, Indianapolis, IN, USA.

Hannah, R., Michaelraj, A., & Summers, J. D. (2008). *A Proposed Taxonomy for Physical Prototypes: Structure and Validation*. Paper presented at the Proceedings of the ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2008, Brooklyn, New York, USA.

Hannapel, S., & Vlahopoulos, N. (2014). Implementation of set-based design in multidisciplinary design optimization. *Structural and Multidisciplinary Optimization, 50*(1), 101-112.

Hannapel, S. E., Vlahopoulos, N., & Singer, D. J. (2012). *Including principles of set-based design in multidisciplinary design optimization*. Paper presented at the Proceedings of the 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and

14th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Indianapolis, IN, USA.

Haque, B., & James-moore, M. (2004). Applying lean thinking to new product introduction. *Journal of Engineering Design, 15*(1), 1-31.

Hart, C. (1998). *Doing a literature review: Releasing the social science research imagination*: Sage.

Hauser, J. R., & Clausing, D. (1988). The house of quality. *Harvard Business Review, 3 (May–June)* 63–73.

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

Hegge, H., & Wortmann, J. (1991). Generic bill-of-material: a new product model. *International Journal of Production Economics, 23*(1-3), 117-128.

Heikkinen, T., Stolt, R., Elgh, F., & Andersson, P. (2016). *Automated Producibility Assessment Enabling Set-Based Concurrent Engineering*. Paper presented at the Proceedings of the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering, Parana, Curitiba, Brazil.

Herlem, G., Adragna, P.-A., Ducellier, G., & Durupt, A. (2012). DMU Maturity Management as an Extension of the Core Product Model. In L. Rivest, A. Bouras & B. Louhichi (Eds.), *Product Lifecycle Management: Towards knowledge-rich enterprises. Proceedings of IFIP WG 5.1 International Conference, PLM 2012* (Vol. 388, pp. 192-201). Montreal, QC, Canada: Springer.

Hernandez-Luna, A. A., Moreno-Grandas, D. P., & Wood, K. L. (2010). *Trade-off of fuzzy set-based design parameters*. Paper presented at the Proceedings of the IIE Annual Conference and Expo 2010, Cancun, Mexico.

Hernandez-Luna, A. A., & Wood, K. L. (1994). *A set based concurrent engineering method for parameter design*. Paper presented at the Proceedings of the 7th International Symposium on Artificial Intelligence, Monterrey, Mexico.

Hillström, F. (1994). *On axiomatic design in modular product development.* (Lic.Eng. thesis, Chalmers University of Technology, Goteborg, Sweden).

Hines, P., Francis, M., & Found, P. (2006). Towards lean product lifecycle management: a framework for new product development. *Journal of Manufacturing Technology Management, 17*(7), 866-887.

Hirz, M., Dietrich, W., Gfrerrer, A., & Lang, J. (2013). *Integrated computer-aided design in automotive development*: Springer-Verlag, Berlin Heiderberg, Germany.

Hoepfl, M. C. (1997). Choosing qualitative research: A primer for technology education researchers. *Journal of Technology Education, 9*(1), 47-63.

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management, 25*(2), 420-437.

Hoppmann, J. (2009). *The Lean Innovation Roadmap-A Systematic Approach to Introducing Lean in Product Development Processes and Establishing a Learning Organization.* (PhD Thesis, Technical University of Braunschweig, Braunschweig, Germany).

Hoppmann, J., Rebentisch, E., Dombrowski, U., & Zahn, T. (2011). A Framework for Organizing Lean Product Development. *Engineering Management Journal, 23*(1), 3-15.

Houde, S., & Hill, C. (1997). What do prototypes prototype? In M. Helander, T. Landauer & P. Prabhu (Eds.), *Handbook of Human-Computer Interaction* (2nd ed.). Amsterdam, The Netherlands: Elsevier Science B. V.

Howard, T. J., Culley, S. J., & Dekoninck, E. (2008). Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design studies, 29*(2), 160-180.

Hubka, V., & Eder, W. E. (1987). A scientific approach to engineering design. *Design Studies, 8*(3), 123-137.

Hubka, V., & Eder, W. E. (2012a). *Design science: introduction to the needs, scope and organization of engineering design knowledge*: Springer Science & Business Media.

Hubka, V., & Eder, W. E. (2012b). *Theory of technical systems: a total concept theory for engineering design*: Springer Science & Business Media.

Huet, G., Fortin, C., McSorley, G., & Toche, B. (2010). *Information structures and processes to support data exchange between product development and resource planning systems*. Paper presented at the Proceedings of the IESM'09 International Conference on Industrial Engineering and Systems Management, Montreal, Quebec, Canada.

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

Huet, G., McAlpine, H., Camarero, R., Culley, S. J., Leblanc, T., & Fortin, C. (2009). *The management of digital sketches through PLM solutions*. Paper presented at the Proceedings of the 17th International Conference on Engineering Design, ICED 09. DS 58-8: Design Information and Knowledge, Palo Alto, CA, USA.

Hyvönen, E. (1992). Constraint reasoning based on interval arithmetic: the tolerance propagation approach. *Artificial Intelligence, 58*(1-3), 71-112.

Inoue, M., Lindow, K., Stark, R., Tanaka, K., Nahm, Y.-E., & Ishikawa, H. (2012). Decision-making support for sustainable product creation. *Advanced Engineering Informatics, 26*(4), 782-792.

Inoue, M., Nahm, Y.-E., Okawa, S., & Ishikawa, H. (2010). Design support system by combination of 3D-CAD and CAE with preference set-based design method. *Concurrent Engineering, 18*(1), 41-53.

Inoue, M., Nahm, Y.-E., Tanaka, K., & Ishikawa, H. (2013a). Collaborative engineering among designers with different preferences: Application of the preference set-based design to the design problem of an automotive front-side frame. *Concurrent Engineering Research and Applications, 21*(4), 252-267.

Inoue, M., Nahm, Y.-E., Tanaka, K., & Ishikawa, H. (2013b). Decision-Making Support for Selection of Design Ideas at the Early Phase of Structural Design. In J. Stjepandić, G.

Rock & C. Bil (Eds.), *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment* (pp. 521-532): Springer, London.

Ishikawa, H., & Inoue, M. (2009). *Set-Based FEM for Product Design With Uncertainties*. Paper presented at the Proceedings of the ASME 2009 International Mechanical Engineering Congress and Exposition (IMECE2009), Lake Buena Vista, Fla, USA.

Ishikawa, H., & Nahm, Y.-E. (2005). *Set-based design methodology and its application to design of automobile body*. Paper presented at the Proceedings of the 12th ISPE International Conference on Concurrent Engineering: Research and Applications - Next Generation Concurrent Engineering: Smart and Concurrent Integration of Product Data, Services, and Control Strategies, CE 2005, Fort Worth, TX, USA.

Jarratt, T., Clarkson, J., & Eckert, C. (2005). Engineering change. In J. Clarkson & C. Eckert (Eds.), *Design process improvement : a review of current practice* (pp. 262-285). London, UK: Springer.

Jepsen, D. M., & Rodwell, J. J. (2008). Convergent interviewing: a qualitative diagnostic technique for researchers. *Management research news, 31*(9), 650-658.

Jiao, J. R., Simpson, T. W., & Siddique, Z. (2007). Product family design and platform-based product development: a state-of-the-art review. *Journal of intelligent Manufacturing, 18*(1), 5-29.

Johannesson, H., & Claesson, A. (2005). Systematic product platform design: a combined function-means and parametric modeling approach. *Journal of Engineering Design, 16*(1), 25-43.

Johannesson, H., Landahl, J., Levandowski, C., & Raudberget, D. (2017). Development of product platforms: Theory and methodology. *Concurrent Engineering, 25*(3), 195 - 211.

Jupp, J. R. (2016). Cross industry learning: a comparative study of product lifecycle management and building information modelling. *International Journal of Product Lifecycle Management, 9*(3), 258-284.

Kamps, J., Monz, C., De Rijke, M., & Sigurbjörnsson, B. (2003). *Language-dependent and language-independent approaches to cross-lingual text retrieval*. Paper presented at the

Workshop of the Cross-Language Evaluation Forum for European Languages, CLEF2001, Darmstadt, Germany.

Karlsson, C., & Ahlström, P. (1996). The difficult path to lean product development. *Journal of Product Innovation Management, 13*(4), 283-295.

Kawakami, M., Kami, Y., Ishikawa, H., & Xiao, F. (2016). Application of the preference set-based design method to filter design. *IEEJ Transactions on Fundamentals and Materials, 136*(10), 621-628.

Kennedy, B. M., Sobek, D. K., & Kennedy, M. N. (2014). Reducing Rework by Applying Set-Based Practices Early in the Systems Engineering Process. *Systems Engineering, 17*(3), 278-296.

Kennedy, M. N. (2003). *Product development for the lean enterprise : Why Toyota's system is four times more productive and how you can implement it.* Richmond, VA: Oaklea Press.

Kerga, E., Khan, M. S., & Arias, A. B. (2012). *Advanced process planning in lean product and process development*. Paper presented at the Proceedings of the 18th International Conference on Engineering, Technology and Innovation, ICE 2012, Munich, Germany.

Kerga, E., Rossi, M., Taisch, M., & Terzi, S. (2014a). A serious game for introducing set-based concurrent engineering in industrial practices. *Concurrent Engineering Research and Applications, 22*(4), 333-346.

Kerga, E., Rossi, M., Terzi, S., Taisch, M., Bessega, W., & Rosso, A. (2014b). Teaching set-based concurrent engineering to practitioners through gaming. *International Journal of Product Development, 19*(5-6), 348-365.

Kerga, E., Taisch, M., & Terzi, S. (2012). Manufacturing process planning in set-based concurrent engineering paradigm. In L. Rivest, A. Bouras & B. Louhichi (Eds.), *Product Lifecycle Management: Towards knowledge-rich enterprises. Proceedings of IFIP WG 5.1 International Conference, PLM 2012* (Vol. 388, pp. 158-169). Montreal, QC, Canada: Springer.

Kerga, E., Taisch, M., & Terzi, S. (2013). *Set Based Concurrent Engineering Innovation Roadmap*. Paper presented at the Proceedings of the IFIP WG 5.7 International

Conference, APMS 2013, Advances in Production Management Systems. Sustainable Production and Service Supply Chains, State College, PA, USA.

Khan, M. S. (2012). *The construction of a model for lean product development.* (PhD Thesis, Cranfield University, Cranfield, UK).

Khan, M. S., Al-Ashaab, A., Doultsinou, A., Shehab, E., Ewers, P., & Sulowski, R. (2011). Set-Based Concurrent Engineering process within the LeanPPD environment. In D. D. Frey, S. Fukuda & G. Rock (Eds.), *Improving Complex Systems Today: Proceedings of the 18th ISPE International Conference on Concurrent Engineering* (pp. 433-440). Boston, MA, USA: Springer-Verlag London.

Khan, M. S., Al-Ashaab, A., Shehab, E., Haque, B., Ewers, P., Sorli, M., & Sopelana, A. (2013). Towards lean product and process development. *International Journal of Computer Integrated Manufacturing, 26*(12), 1105-1116.

Kidd, P. T. (1996). *Agile manufacturing: a strategy for the 21st century*. Paper presented at the IEE Colloquium on Agile Manufacturing, Cranfield, UK.

Kim, B.-Y., & Kang, B.-K. (2008). Cross-functional cooperation with design teams in new product development. *International Journal of Design, 2*(3), 43-54.

Kizer, J. R., & Mavris, D. N. (2014). *Set-based design space exploration enabled by dynamic constraint analysis*. Paper presented at the Proceedings of the 29th Congress of the International Council of the Aeronautical Sciences, ICAS 2014, St. Petersburg, Russia.

Konda, S., Monarch, I., Sargent, P., & Subrahmanian, E. (1992). Shared memory in design: a unifying theme for research and practice. *Research in Engineering design, 4*(1), 23-42.

Krafcik, J. F. (1986). *Learning from NUMMI*: International Motor Vehicle Program (IMVP), MIT, Cambridge, USA.

Krafcik, J. F. (1988). Triumph of the lean production system. *MIT Sloan Management Review, 30*(1), 41.

Krishnan, V., & Ulrich, K. T. (2001). Product development decisions: A review of the literature. *Management science, 47*(1), 1-21.

Kuhn, T. S. (1970). The structure of scientific revolutions. In *International Encyclopedia of Unified Science* (Vol. 2, no. 2). Chicago: The University of Chicago Press.

Landahl, J., Levandowski, C., Johannesson, H., & Isaksson, O. (2016). *Assessing Producibility of Product Platforms Using Set-Based Concurrent Engineering*. Paper presented at the Proceedings of the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering, Curitiba, Parana, Brazil.

Landahl, J., Raudberget, D., & Johannesson, H. (2015). *Assessing System Maturity of Interacting Product and Manufacturing Alternatives Before Early Technology Commitment*. Paper presented at the Proceedings of the 24th International Association for Management of Technology Conference, IAMOT 2015, Cape Town, South Africa.

Larman, C., & Basili, V. R. (2003). Iterative and incremental developments. a brief history. *Computer, 36*(6), 47-56.

Lazzari, D., & Raimondo, G. (2001). *Digital Mock-Up in support to Space Station elements Integration and Test*. Paper presented at the Proceedings of the 4th International Symposium on Environmental Testing for Space Programmes, Liege, Belgium.

Lemieux, A.-A., Pellerin, R., & Lamouri, S. (2013). A mixed performance and adoption alignment framework for guiding leanness and agility improvement initiatives in product development. *Journal of Enterprise Transformation, 3*(3), 161-186.

Lenarduzzi, V., & Taibi, D. (2016). *MVP Explained: A Systematic Mapping Study on the Definitions of Minimal Viable Product*. Paper presented at the Proceedings of the 42th Euromicro Conference on Software Engineering and Advanced Applications, SEAA 2016 Limassol, Cyprus.

León, H. C. M., & Farris, J. A. (2011). Lean Product Development Research: Current State and Future Directions. *Engineering Management Journal, 23*(1), 29-51.

Levandowski, C. (2014). *Platform lifecycle support using set-based concurrent engineering.* (PhD Thesis, Chalmers University of Technology, Göteborg, Sweden).

Levandowski, C., Forslund, A., Söderberg, R., & Johannesson, H. (2013). *Using PLM and trade-off curves to support set-based convergence of product platforms*. Paper presented at the

Proceedings of the 19th International Conference on Engineering Design, ICED 2013, Seoul, Korea (South).

Levandowski, C., Michaelis, M. T., & Johannesson, H. (2014a). Set-based development using an integrated product and manufacturing system platform. *Concurrent Engineering, 22*(3), 234-252.

Levandowski, C., Müller, J. R., & Isaksson, O. (2016). *Modularization in Concept Development Using Functional Modeling*. Paper presented at the Proceedings of the 23rd ISPE Inc. International Conference on Transdisciplinary Engineering, Curitiba, Parana, Brazil.

Levandowski, C., Raudberget, D. S., & Johannesson, H. (2014b). *Set-Based Concurrent Engineering for Early Phases in Platform Development*. Paper presented at the Proceedings of the 21st ISPE International Conference on Concurrent Engineering, CE2014, Beijing, China.

Liker, J. K. (2004). *The Toyota Way*: McGraw-Hill.

Liker, J. K., & Morgan, J. M. (2006). The Toyota way in services: the case of lean product development. *The Academy of Management Perspectives, 20*(2), 5-20.

Liker, J. K., Sobek II, D. K., Ward, A. C., & Cristiano, J. J. (1996). Involving suppliers in product development in the United States and Japan: Evidence for set-based concurrent engineering. *IEEE Transactions on Engineering Management, 43*(2), 165-178.

Lindlöf, L., Söderberg, B., & Persson, M. (2013). Practices supporting knowledge transfer – an analysis of lean product development. *International Journal of Computer Integrated Manufacturing, 26*(12), 1128-1135.

Liu, B., Campbell, R., & Pei, E. (2013). Real-time integration of prototypes in the product development process. *Assembly Automation, 33*(1), 22-28.

Liu, W., Zeng, Y., Maletz, M., & Brisson, D. (2009). *Product lifecycle management: A survey*. Paper presented at the Proceedings of the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2009, San Diego, CA, USA.

Lloyd, P. (2000). Storytelling and the development of discourse in the engineering design process. *Design studies, 21*(4), 357-373.

Lloyd, P., & Deasley, P. (1998). Ethnographic description of design networks. *Automation in construction, 7*(2-3), 101-110.

Loch, C. H., & Terwiesch, C. (1998). Communication and uncertainty in concurrent engineering. *Management Science, 44*(8), 1032-1048.

Lorisson, J. (2010). Réalité virtuelle dans l'industrie-Développement des produits et des processus - Virtual Reality in industry-Product and process development (In French). *Techniques de l'ingénieur TE, 5*(2010), 965.

MacDuffie, J. P., & Krafcik, J. (1992). Integrating technology and human resources for high-performance manufacturing: Evidence from the international auto industry. In T. A. Kochan & M. Useem (Eds.), *Transforming organizations* (pp. 209-226): New York: Oxford University Press.

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

Malmqvist, J. (1997). Improved function-means trees by inclusion of design history information. *Journal of Engeering Design, 8*(2), 107-117.

Männistö, T. (2000). *A conceptual modelling approach to product families and their evolution.* (PhD Thesis, Helsinki University of Technology, Helsinki, Finland).

Männistö, T., Peltonen, H., Soininen, T., & Sulonen, R. (2001). Multiple abstraction levels in modelling product structures. *Data & Knowledge Engineering, 36*(1), 55-78.

Mas, F., Menéndez, J., Oliva, M., Gómez, A., & Ríos, J. (2013a). Collaborative engineering paradigm applied to the aerospace industry. In A. Bernard, L. Rivest & D. Dutta (Eds.), *Product Lifecycle Management for society. 10th IFIP 5.1 International Conference, PLM 2013* (Vol. 409, pp. 675-684). Nantes, France: Springer.

Mas, F., Menendez, J. L., Oliva, M., & Rios, J. (2013b). Collaborative Engineering: an Airbus case study. *Procedia Engineering, 63*(2013), 336-345.

Mas, F., Menendez, J. L., Oliva, M., Rios, J., Gomez, A., & Olmos, V. (2014). *iDMU as the Collaborative Engineering engine: Research experiences in Airbus*. Paper presented at the Proceedings of the 20th International Conference on Engineering, Technology and Innovation: Engineering Responsible Innovation in Products and Services, ICE 2014, Bergamo, Italy.

Matthews, J., Klatt, T., Seepersad, C. C., Haberman, M., & Shahan, D. (2014). *Bayesian network classifiers and design flexibility metrics for setbased, multiscale design with materials design applications*. Paper presented at the Proceedings of the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2014, Buffalo, NY, USA.

Maulana, M. I. I. M., Flisiak, J. W., Al-Ashaab, A., Araci, Z. C., Lasisz, P. W., Beg, N., & Rehman, A. (2016). The Application of Set-Based Concurrent Engineering to Enhance the Design Performance of Surface Jet Pump. *WSEAS Transactions on Business and Economics, 13*(2016), 634-643.

Maurino, M. (1993). *La gestion des données techniques: technologie du concurrent engineering - Product Data Management: Technology for concurrent engineering (In French)*. Paris, France: Masson.

Maxwell, J. A. (2012). *Qualitative research design: An interactive approach* (2nd ed.): Sage publications.

McKenney, T., & Singer, D. (2014). Set-Based Design: A concurrent engineering approach with particular application to complex marine products. *Marine Technology, 51*(3), 51-55.

McKenney, T. A., Gray, A. W., Madrid, C., & Singer, D. J. (2011). *The use of a fuzzy logic set-based design tool to evaluate varying complexities of late-stage design changes*. Paper presented at the Proceedings of the 2011 International Conference on Computer Applications in Shipbuilding, Trieste, Italy.

McKenney, T. A., Kemink, L. F., & Singer, D. J. (2011). Adapting to Changes in Design Requirements Using Set-Based Design. *Naval Engineers Journal, 123*(3), 66-77.

McMahon, C., & Browne, J. (1993). *CAD/CAM From principles to practice*. Wokingham: Addison-Wesley Publishing Company.

McManus, H. L., Haggerty, A., & Murman, E. (2005). *Lean engineering: doing the right thing right*. Paper presented at the 1st International Conference on Innovation and Integration in Aerospace Sciences, Queen's University Belfast, Northern Ireland, UK.

McSorley, G. (2014). *A novel approach to product lifecycle management and engineering based on product in-use information.* (PhD Thesis, École Polytechnique de Montréal, Montreal, QC, Canada).

Menéndez, J., Mas, F., Servan, J., Arista, R., & Ríos, J. (2013). Implementation of the iDMU for an Aerostructure Industrialization in AIRBUS. *Procedia Engineering, 63*(2013), 327-335.

Menendez, J., Mas, F., Servan, J., & Rios, J. (2012). Virtual verification of an aircraft Final Assembly Line industrialization: an industrial case. In M. Marcos, J. Salguero & A. Pastor (Eds.), *Key Engineering Materials: Advances in Manufacturing Systems* (Vol. 502, pp. 139-144): Trans Tech Publications Ltd.

Mesihovic, S., & Malmqvist, J. (2004). *A process-oriented approach for management of product configuration models*. Paper presented at the Proceedings of the ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC 2004, Salt Lake City, Utah, USA.

Michaelis, M. T., Levandowski, C., & Johannesson, H. (2013). *Set-based concurrent engineering for preserving design bandwidth in product and manufacturing system platforms*. Paper presented at the Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition, IMECE2013, San Diego, CA, USA.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*: Sage Publications.

MilitarySpecification. (1959). *MIL-E-22285 (Wep), Extinguishing System, Fire, Aircraft, High-Rate-Discharge Type, Installation and Test of.* Washington DC, USA, Amendment – 1, 27 April 1960.

Morgan, J. M. (2002). *High performance product development: A systems approach to a lean product development process.* (PhD Thesis, University of Michigan, Ann Arbor, MI, USA).

Morgan, J. M., & Liker, J. K. (2006). *The Toyota Product Development System: Integrating people, process, and technology*. New York, NY: Productivity Press.

Moshaiov, A., & Avigad, G. (2007). *Concept-based multi-objective problems and their solution by EC*. Paper presented at the Proceedings of the 9th Annual Genetic and Evolutionary Computation Conference, GECCO 2007, London, UK.

Mukherjee, S. K., Ryan, J. L., & Wason, J. R. (1994). Method and system for product configuration definition and tracking, U.S. Patent No. 5,311,424. Washington, DC: U.S.: Patent and Trademark Office.

Mulrow, C. D. (1994). Rationale for Systematic Reviews. *BMJ: British Medical Journal, 309*(6954), 597-599.

Murman, E., Allen, T., Bozdogan, K., Cutcher-Gershenfeld, J., McManus, H., Nightingale, D., Rebentisch, E., Shields, T., Stahl, F., Walton, M., Warmkessel, J., Weiss, S., & Widnall, S. (2002). *Lean enterprise value: Insights From MIT's Lean Aerospace inititiative*. New York: Palgrave Macmillan.

Nahm, Y.-E., & Ishikawa, H. (2005). Representing and aggregating engineering quantities with preference structure for set-based concurrent engineering. *Concurrent Engineering Research and Applications, 13*(2), 123-133.

Nahm, Y.-E., & Ishikawa, H. (2006a). A new 3D-CAD system for set-based parametric design. *The International Journal of Advanced Manufacturing Technology, 29*(1), 137-150.

Nahm, Y.-E., & Ishikawa, H. (2006b). Novel space-based design methodology for preliminary engineering design. *The International Journal of Advanced Manufacturing Technology, 28*(11), 1056-1070.

Nahm, Y.-E., Ishikawa, H., & Yang, Y.-S. (2007). A flexible and robust approach for preliminary engineering design based on designer's preference. *Concurrent Engineering, 15*(1), 53-62.

Neeley, W. L., Lim, K., Zhu, A., & Yang, M. C. (2013). *Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design*. Paper presented at the Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2013, Portland, OR, USA.

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

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

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

Ong, S., Sun, M., & Nee, A. (2003). A fuzzy set AHP-based DFM tool for rotational parts. *Journal of Materials Processing Technology, 138*(1), 223-230.

Ong, S. K., & Nee, A. Y. C. (1998). A systematic approach for analyzing the fixturability of parts for machining. *Transactions of the ASME. Journal of Manufacturing Science and Engineering, 120*(2), 401-408.

Oppenheim, B. W. (2004). Lean product development flow. *Systems Engineering, 7*(4), 352-376.

Oppenheim, B. W., Murman, E. M., & Secor, D. A. (2011). Lean enablers for systems engineering. *Systems Engineering, 14*(1), 29-55.

Orr, W. M., Panuganti, B. N., Ryan, J. L., Sambataro, G. J., & Wason, J. R. (1993). Engineering and manufacturing change control mechanism, U.S. Patent No 5,191,534. Washington, DC: U.S.: Patent and Trademark Office.

Otto, K. N., & Antonsson, E. K. (1995). Imprecision in engineering design. *ASME J. Mech. Des, 117*(B), 25-32.

Otto, K. N., & Wood, K. L. (2001). *Product Design: Techniques in Reverse Engineering and New Product Development*. Upper Saddle River, NJ: Prentice Hall.

Ottosson, S. (2002). Virtual reality in the product development process. *Journal of Engineering Design, 13*(2), 159-172.

Pahl, G., & Beitz, W. (2013). *Engineering design: a systematic approach*: Springer Science & Business Media.

Paillé, P., & Mucchielli, A. (2016). *L'analyse qualitative en sciences humaines et sociales. Qualitative inquiry in human and social sciences (In French)* (4 ed.): Armand Colin.

Panchal, J. H., Gero Fernández, M., Paredis, C. J., Allen, J. K., & Mistree, F. (2007). An interval-based constraint satisfaction (IBCS) method for decentralized, collaborative multifunctional design. *Concurrent Engineering, 15*(3), 309-323.

Panchenko, Y., Moustapha, H., Mah, S., Patel, K., Dowhan, M. J., & Hall, D. (2002). *Preliminary multi-disciplinary optimization in turbomachinery design*. Paper presented at the Proceeding of the RTO AVT Symposium on "Reduction of Military Vehicle Aquisition Time and Cost through Advanced Modelling and Virtual Simulation", Paris, France.

Parrish, K. D. (2009). *Applying a set-based design approach to reinforcing steel design.* (PhD Thesis, University of California, Berkeley, USA).

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

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

Patton, M. Q. (1990). *Qualitative evaluation and research methods*: SAGE Publications.

Peltonen, H., Männistö, T., Soininen, T., Tiihonen, J., Martio, A., & Sulonen, R. (1998). Concepts for modeling configurable products. In *Proceedings of the Product Data Technology Days* (pp. 189-196). Sandhurst, UK: Quality Marketing Services.

Pinquié, R., Rivest, L., Segonds, F., & Véron, P. (2015). An illustrated glossary of ambiguous PLM terms used in discrete manufacturing. *International Journal of Product Lifecycle Management, 8*(2), 142-171.

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

Prasad, B. (1996). *Concurrent engineering fundamentals* (Vol. 1): Prentice Hall Englewood Cliffs, NJ.

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

Qureshi, A. J., Dantan, J.-Y., Bruyere, J., & Bigot, R. (2010). Set based robust design of mechanical systems using the quantifier constraint satisfaction algorithm. *Engineering Applications of Artificial Intelligence, 23*(7), 1173-1186.

Qureshi, A. J., Dantan, J.-Y., Bruyere, J., & Bigot, R. (2014). Set-based design of mechanical systems with design robustness integrated. *International Journal of Product Development, 19*(1-3), 64-89.

Radkowski, R. (2011). Towards semantic virtual prototypes for the automatic model combination. In A. Bernard (Ed.), *Global Product Development. Proceedings of the 20th CIRP Design Conference* (pp. 307-318). Nantes, France: Springer.

Raudberget, D. S. (2010a). *The decision process in Set-based Concurrent Engineering-An industrial case study*. Paper presented at the Proceedings of the 11th International Design Conference, DESIGN 2010, Dubrovnik, Croatia.

Raudberget, D. S. (2010b). Practical applications of set-based concurrent engineering in industry. *Journal of Mechanical Engineering, 56*(11), 685-695.

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

Raudberget, D. S. (2015). *Industrial Application of Set-based Concurrent Engineering–Managing the design space by using Platform System Families.* (PhD Thesis, Chalmers University of Technology, Göteborg, Sweden).

Raudberget, D. S., Michaelis, M. T., & Johannesson, H. (2014). *Combining set-based concurrent engineering and function—Means modelling to manage platform-based product family design*. Paper presented at the Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2014, Selangor, Malaysia.

Raudberget, D. S., & Sunnersjö, S. (2010). *Experiences of set based concurrent engineering in four product developing companies*. Paper presented at the Proceedings of the 8th International Symposium on Tools and Methods of Competitive Engineering, TMCE 2010, Ancona, Italy.

Rebentisch, E. (2008). *Lean Product Development in the Aerospace Enterprise*. Paper presented at the Proceedings of the 26th Congress of the International Council of the Aeronautical Sciences, ICAS 2008, Anchorage, AK, USA.

Reich, Y. (1995). The study of design research methodology. *Journal of Mechanical Design, Transactions of the ASME, 117*(2), 211-214.

Reinertsen, D. (2007). Rethinking lean NPD. *Strategic directions, 23*(10), 32-34.

Reinertsen, D., & Smith, P. (1991). *Developing products in half the time* (2nd ed.). New York: Wiley.

Riel, A., & Brenner, E. (2004). *Simulation Interoperability in Product Development*. Paper presented at the Proceedings of the 2004 European Simulation Interoperability Workshop (EURO-SIW), Edinburgh, Scotland.

Rocha, H. M., Affonso, L. M. F., & De Oliveira, U. L. R. (2012). New Product Development using Set-based Concurrent Engineering (SBCE). In *Decision Making Systems in Business Administration* (Vol. 8, pp. 421-430): World Scientific Publishing.

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

Rother, M., & Shook, J. (2003). *Learning to see: Value stream mapping to add value and eliminate muda*. Cambridge, MA: Lean Enterprise Institute.

Ryan, R. R. (1999). Digital Testing in the Context of Digital Engineering - Functional Virtual Prototyping. *VDI Berichte, 1489*(1999), 163-186.

Sääksvuori, A., & Immonen, A. (2004). *Product Lifecycle Management* Berlin: Springer-Verlag.

Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. *European journal of operational research, 48*(1), 9-26.

Sabin, D., & Weigel, R. (1998). Product configuration frameworks-a survey. *IEEE Intelligent Systems and their applications, 13*(4), 42-49.

Salehi, V., & Wang, S. (2017). *Using point cloud technology for process simulation in the context of digital factory based on a systems engineering integrated approach*. Paper presented at the Proceedings of the 21st International Conference on Engineering Design, ICED 17, Vancouver, BC, Canada.

Sasaki, N., & Ishikawa, H. (2015). Set-based Design Method for Multi-objective Structural Design with Conflicting Performances Under Topological Change. *Procedia CIRP, 26*(2015), 76-81.

Schafer, H., & Sorensen, D. J. (2010). Creating options while designing prototypes: Value management in the automobile industry. *Journal of Manufacturing Technology Management, 21*(6), 721-742.

Schneider, P., Clauß, C., Enge-Rosenblatt, O., Schneider, A., Bruder, T., Schäfer, C., Voigt, L., Stork, A., & Farkas, T. (2010). *Functional Digital Mock-up-More Insight to Complex Multi-physical Systems*. Paper presented at the Proceedings of the 1st Conference on Multiphysics Simulation–Advanced Methods for Industrial Engineering., Bonn, Germany.

Schonberger, R. J. (2007). Japanese production management: An evolution—With mixed success. *Journal of Operations Management, 25*(2), 403-419.

Schwaber, K. (1997). Scrum development process. In J. Sutherland, C. Casanave, J. Miller, P. Patel & G. Hollowell (Eds.), *Business Object Design and Implementation* (pp. 117-134): Springer, London.

Shahan, D., & Seepersad, C. C. (2009). *Bayesian networks for set-based collaborative design*. Paper presented at the Proceedings of the ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2009, San Diego, CA, USA.

Shahan, D., & Seepersad, C. C. (2010). Implications of alternative multilevel design methods for design process management. *Concurrent Engineering, 18*(1), 5-18.

Shahan, D., & Seepersad, C. C. (2012). Bayesian network classifiers for set-based collaborative design. *Journal of Mechanical Design, Transactions of the ASME, 134*(7), 0710011-07100114.

Shan, S., & Wang, G. G. (2003). *Introducing rough set for design space exploration and optimization*. Paper presented at the Proceedings of the ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC 2003, Chicago, IL, USA.

Smith, R. (1991). Where is the Wisdom...? The poverty of medical evidence. *BMJ: British Medical Journal, 303*(6806), 798-799.

Sobek, D. K. (1996a). Set-based model of design. *Mechanical Engineering, 118*(7), 78-81.

Sobek, D. K. (1996b). *Set-based model of design: the case of Toyota*. Paper presented at the Proceedings of the 1996 National Design Engineering Conference, Chicago, IL, USA.

Sobek, D. K., & Ward, A. C. (1996). *Principles from Toyota's Set-Based Concurrent Engineering Process*. Paper presented at the Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, DETC 1996, Irvine, CA, USA.

Sobek, D. K., Ward, A. C., & Liker, J. K. (1999). Toyota's Principles of Set-Based Concurrent Engineering. *Sloan Management Review, 40*(2), 67-83.

Soininen, T., Tiihonen, J., Männistö, T., & Sulonen, R. (1998). Towards a general ontology of configuration. *AI EDAM, 12*(4), 357-372.

Spear, S., & Bowen, H. K. (1999). Decoding the DNA of the Toyota production system. *Harvard business review, 77*(5), 96-106.

Stark, J. (2015). *Product Lifecycle Management (Volume 1): 21st Century Paradigm for Product Realisation*. Switzerland: Springer International Publishing.

Stark, R., Hayka, H., Figge, A., & Woll, R. (2011). Interdisciplinary function-oriented design and verification for the development of mechatronical products. In A. Bernard (Ed.), *Global Product Development. Proceedings of the 20th CIRP Design Conference* (pp. 299-306). Nantes, France: Springer.

Steward, D. V. (1981). The design structure system: A method for managing the design of complex systems. *IEEE transactions on Engineering Management, 28*(3), 71-74.

Stewart, D. W., & Shamdasani, P. N. (2014). *Focus groups: Theory and practice*: Sage Publications.

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

Sugimori, Y., Kusunoki, K., Cho, F., & Uchikawa, S. (1977). Toyota Production System and Kanban System. Materialization of Just-in-Time and Respect-for-Human System. *International Journal of Production Research, 15*(6), 553-564.

Suh, N. P. (1990). *The principles of design*. New York: Oxford University Press.

Suh, N. P. (2001). *Axiomatic Design: Advances and Applications. The Oxford Series on Advanced Manufacturing*. New York: Oxford University Press.

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

Svensson, D., & Malmqvist, J. (2001). *Integration of requirement management and product data management systems*. Paper presented at the Proceedings of the ASME2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2001, Pittsburgh, PA, USA.

Svensson, D., & Malmqvist, J. (2002). Strategies for product structure management at manufacturing firms. *Journal of Computing and Information Science in Engineering, 2*(1), 50-58.

Takai, S. (2010). A lifecycle-cost model for set-based concept testing. *Concurrent Engineering, 18*(2), 121-127.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2017). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology*. doi:10.1007/s00170-017-0233-1

Taylor, E. (1959). *An interim report on engineering design*. Cambridge, MA, USA: Massachusetts Institute of Technology.

Terwiesch, C., & Loch, C. H. (1999). Measuring the effectiveness of overlapping development activities. *Management science, 45*(4), 455-465.

Terwiesch, C., Loch, C. H., & Meyer, A. D. (2002). Exchanging preliminary information in concurrent engineering: Alternative coordination strategies. *Organization Science, 13*(4), 402-419.

Terzi, S., Bouras, A., Dutta, D., Garetti, M., & Kiritsis, D. (2010). Product lifecycle management–from its history to its new role. *International Journal of Product Lifecycle Management, 4*(4), 360-389.

Thomke, S. (2008). Learning by experimentation: Prototyping and testing. In C. H. Loch & S. Kavadias (Eds.), *Handbook of new product development management* (pp. 401-420). Amsterdam, The Netherlands: Elsevier : Butterworth-Heinemann.

Thomke, S., & Reinertsen, D. (1998). Agile product development: Managing development flexibility in uncertain environments. *California management review, 41*(1), 8-30.

Thurston, D. L. (1990). Multiattribute utility analysis in design management. *IEEE Transactions on Engineering Management, 37*(4), 296-301.

Tiihonen, J., Lehtonen, T., Soininen, T., Puikkinen, A., Sulonen, R., & Riitahuhta, A. (1998). *Modeling configurable product families*. Paper presented at the Proceedings of the 4th WDK Workshop on Product Structuring, Delft, Germany.

Toche, B., Huet, G., & Fortin, C. (2011). *The management of prototyping and testing information from a product lifecycle perspective.* Paper presented at the Proceedings of the Canadian Aeronautics and Space Institute AERO 2011 Conference, CASI Aircraft Design and Development Symposium, Montreal, QC, Canada.

Toche, B., Huet, G., McSorley, G., & Fortin, C. (2010). *A Product Lifecycle Management Framework to Support the Exchange of Prototyping and Testing Information*. Paper presented at the Proceedings of the ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE 2010, Montreal, QC, Canada.

Toche, B., Pellerin, R., Fortin, C., & Huet, G. (2012). Set-based prototyping with digital mock-up technologies. In L. Rivest, A. Bouras & B. Louhichi (Eds.), *Product Lifecycle Management: Towards knowledge-rich enterprises. Proceedings of IFIP WG 5.1 International Conference, PLM 2012* (Vol. 388, pp. 299-309). Montreal, QC, Canada: Springer.

Tommelein, I. D. (1989). *SightPlan: An expert system that models and augments human decision-making for designing construction site layouts.* (PhD Thesis, Stanford University, Stanford, CA, USA).

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British journal of management, 14*(3), 207-222.

Trochim, W. M., & Donnelly, J. P. (2000). *Research methods knowledge base* (2nd ed.). Cincinnati, OH: Atomic Dog Publishing.

Ullman, D. G. (2001). Robust decision-making for engineering design. *Journal of Engineering Design, 12*(1), 3-13.

Ullman, D. G. (2009). *The mechanical design process* (4th ed.). New York, NY: McGraw-Hill Higher Education.

Ulrich, K. T., & Eppinger, S. D. (2012). *Product design and development* (5th ed.). Boston, Massachusetts: McGraw-Hill Higher Education.

Van Den Hamer, P., & Lepoeter, K. (1996). Managing design data: The five dimensions of CAD frameworks, configuration management, and product data management. *Proceedings of the IEEE, 84*(1), 42-56.

Van Der Auweraer, H., & Leuridan, J. (2005). A new testing paradigm for today's product development process - Part 1. *Sound and Vibration, 39*(9), 14-18.

Van Veen, E. A. (1991). *Modelling product structures by generic bills-of-materials.* (PhD Thesis, Technische Universiteit Eindhoven, The Netherlands).

Van Veen, E. A., & Wortmann, J. C. (1992). New developments in generative BOM processing systems. *Production Planning & Control, 3*(3), 327-335.

Vosgien, T. (2015). *Model-based system engineering enabling design-analysis data integration in digital design environments: application to collaborative aeronautics simulation-based design process and turbojet integration studies.* (Doctoral Dissertation, Ecole Centrale Paris, Paris, France).

Wahl, A., & Johannesson, H. (2010). *Managing Design Change in Configurable Component Based Product Platforms*. Paper presented at the Proceedings of the 8th International NordDesign Conference, NordDesign 2010, Göteborg, Sweden.

Wang, G. G. (2002). Definition and Review of Virtual Prototyping. *Journal of Computing and Information Science in Engineering, 2*(3), 232–236.

Wang, G. G., & Shan, S. (2004). *Design space reduction for multi-objective optimization and robust design optimization problems*. Paper presented at the Proceedings of the 2004 SAE World Congress, Detroit, MI, USA.

Wang, J., Yannou, B., Alizon, F., & Yvars, P.-A. (2013). A usage coverage-based approach for assessing product family design. *Engineering with Computers, 29*(4), 449-465.

Ward, A. C. (1989). *A theory of Quantitative inference for artifact sets applied to a mechanical design compiler.* (Doctor of Science Dissertation, Massachusetts Institute of Technology, Cambridge, MA, USA). (DTIC Document No. AI-TR-1089)

Ward, A. C., Liker, J. K., Cristiano, J. J., & Sobek, D. K. (1995). The second Toyota paradox: How delaying decisions can make better cars faster. *Sloan Management Review, 36*(3), 43-61.

Ward, A. C., Liker, J. K., Sobek, D. K., & Cristiano, J. J. (1994). Set-based concurrent engineering and Toyota. In *Proceedings of the 6th International Conference on Design Theory and Methodology. 1994 ASME Design Technical Conferences* (Vol. 68, pp. 79-90). Minneapolis, MN, USA: American Society of Mechanical Engineers.

Ward, A. C., & Sobek, D. K. (2014). *Lean product and process development* (2nd ed.). Cambridge, MA: The Lean Enterprise Institute.

Wasim, A., Shehab, E., Abdalla, H., Al-Ashaab, A., Sulowski, R., & Alam, R. (2013). An innovative cost modelling system to support lean product and process development. *The International Journal of Advanced Manufacturing Technology, 65*(1-4), 165-181.

Watts, F. B. (2012). *Engineering documentation control handbook: configuration management and product lifecycle management*. London, UK: William Andrew.

Waurzyniak, P. (2008). PLM tools speed developments. *Manufacturing Engineering, 140*(6), 101-108.

Waurzyniak, P. (2010). Speeding product development through PLM. *Manufacturing Engineering, 144*(6), 39, 41-45.

Wheelwright, S. C., & Clark, K. B. (1992). *Revolutionizing product development: Quantum leaps in speed, efficiency, and quality.* New York, NY: The Free Press.

Womack, J. P. (2006). A lesson to be learned. *Manufacturing Engineer, 85*(2), 4-5.

Womack, J. P., & Jones, D. T. (1996). *Lean thinking: banish waste and create wealth in your corporation*. New York: Simon and Schuster.

Womack, J. P., Jones, D. T., & Roos, D. (1991). *The Machine that Changed the World: The Story of Lean Production*. New York, NY: HarperCollins.

Wood, K. L., Otto, K. N., & Antonsson, E. K. (1992). Engineering design calculations with fuzzy parameters. *Fuzzy sets and systems, 52*(1), 1-20.

Wortmann, J. C., & Erens, F. (1995). Control of variety by generic product modeling. In *Proceedings of The First World Congress on Intelligent Manufacturing Processes and Systems* (Vol. 2, pp. 1327-1342). Puerto Rico, PR, USA.

Wortmann, J. C., Muntslag, D. R., & Timmermans, P. J. M. (1997). Customer-driven manufacturing. London: Chapman & Hall.

Wynn, D. C. (2007). *Model-based approaches to support process improvement in complex product development.* (PhD Thesis, University of Cambridge, Cambridge, UK).

Yannou, B., Yvars, P.-A., Hoyle, C., & Chen, W. (2013). Set-based design by simulation of usage scenario coverage. *Journal of Engineering Design, 24*(8), 575-603. doi:10.1080/09544828.2013.780201

Yin, R. K. (2013). *Case study research: Design and methods*: Sage publications.

Zhai, L.-Y., Khoo, L.-P., & Zhong, Z.-W. (2009). A rough set based QFD approach to the management of imprecise design information in product development. *Advanced Engineering Informatics, 23*(2), 222-228.

DISCLAIMER

Some commercial software systems are identified herein in order to facilitate understanding. Such identification does not imply that the software systems are necessarily the best available for the purpose. These software systems were made available by courtesy, for educational and research purpose only.