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PRELIMINARY DESIGN ENHANCEMENT BY INCORPORATING SET-BASED DESIGN PRINCIPLES AND A NAVIGATOR

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LIST OF ABBREVIATIONS

CONGA – CONCEPT OPTIMISATION OF NEXT GENERATION AIRCRAFT

LeanPPD – LEAN PROCESS AND PRODUCT DEVELOPMENT

PD – PROCESS DEVELOPMENT

PLM – PRODUCT LIFECYCLE MANAGEMENT

R&D – RESEARCH AND DEVELOPMENT

RDC – ROBUST DESIGN CYCLE

RR-SBD – ROLLS-ROYCE SET-BASED DESIGN

SBCE - SET-BASED CONCURRENT ENGINEERING

SBD – SET-BASED DESIGN

SBD NAVIGATOR – SET-BASED DESIGN NAVIGATOR

SDI – SYSTEM DESIGN INTEGRATION

SDR (0/1) – SYSTEM DESIGN REVIEW (0/1)

TRL – TECHNOLOGY READINESS LEVEL

1. INTRODUCTION

The need for improvement of Product Development (PD) processes has been demonstrated by a high demand for the aerospace products to be developed quicker and cheaper. Set-Based Design (SBD) can improve the ability to respond faster to customers' requirements by developing a set of design solutions for possible future product orders in parallel. In SBD participants practise SBCE (Set-Based Concurrent Engineering) by reasoning, developing and communicating about sets of solutions in parallel. As the design progresses, they gradually narrow their respective sets of solutions based on the knowledge gained. As they narrow, they commit to staying within the sets so that others can rely on their communication (Sobek et al, 1999). This research aims to develop logical guidelines for the selection of the PD tools and methods to enable the effective application of the SBD process model guided by a computerized tool, called 'SBD Navigator'. An integration of the SBD good practices into the collaborator's PD processes is believed to reduce the possibility of the negative design iteration and to reduce PD time thus providing financial benefits. Understanding the selection of PD methods and tools within manufacturing companies is a starting point of this research. It reveals main causes of poor incorporation of PD methods and tools in the preliminary design phase that might stop businesses from gaining a full range of benefits out of the SBD process model. As time goes on, PD becomes more difficult to manage due to the necessity of the collaboration among business participants in order to create complex and well integrated products. This research project has employed one of the deliverables from the CONGA (Concept Optimisation of Next Generation Aircraft) project which is the SBD process model customized by the collaborating company – Rolls-Royce plc. The RR-SBD process model is presented in chapter 3.

This research presents the outcomes of an investigation into how design tools and methods are selected in preliminary design activities within Rolls-Royce plc and opportunities to use a SBD Navigator to improve the selection of design tools and methods in order to enhance the implementation of the RR-SBD process model. The selection of design tools and methods behind the preliminary design activities has been altered by revising best practice within the company and by incorporating novel findings in SBD environment from research projects. A new method of navigating through SBD process model, using platform independent software is proposed which could result in new engine architectures suitable for different aircraft configurations and their novel wing options much quicker and with greater confidence. To sustain competitiveness, a firm has to be innovative as well as quick to respond to the changing customer needs in order to provide better and faster products to market than competitors (Kumar and Phrommathed, 2005).

This research is formed out of 7 chapters that are structured according to the progression of the research conducted. The overview of the contents of the chapters is provided below. Each of the chapters starts with an introduction to present the rationale behind the chapter structure:

- Chapter 1 - Introduction
- Chapter 2 – Literature Review
- Chapter 3 – Rolls-Royce-Set Based design process overview
- Chapter 4 - Design tools and methods selection within RR-SBD process model
- Chapter 5 - The development of a SBD Navigator
- Chapter 6 - SBD Navigator validation
- Chapter 7 – Conclusions and future work

The aim and the objectives listed in this report are the framework of the research that will enable to satisfy the academic and the industrial requirements of it.

1.1 The aim and objectives

The aim of this project is to enhance Set-Based design (SBD) process model via the altered selection of the design tools and methods approach. In addition, to support the development of a novel SBD Navigator to guide the enhanced application of SBD process in Rolls-Royce plc.

1. To synthesise and capture the best practice of product development and the selection of the design tools and methods in SBD environment via extensive literature review.

2. To gather typical industrial requirements to aid the selection of the suitable design tools and methods to enable different activities in order to enhance the application of the SBD process model.

3. To develop the logic of defining and selecting suitable design tools and methods in order to enable/enhance different activities within the current RR-SBD process model.

4. To assist the development of the software demonstrator to guide a customised SBD process model at Rolls-Royce in a form of a computerised software tool called the SBD Navigator. Particularly, in developing the logical guidelines in order to select different design tools and methods within different design activities.

5. To validate the new process model using the SBD Navigator via research based use case study, and expert judgement.

1.2 Research methodology

Figure 1.1 presents the research methodology developed for this thesis

Phase	Key Tasks
1 Background Theory	1.1 Extensive literature review of PD/SBD. 1.2 Understanding existing SBD process model evolution of the collaborative company.
2 SBD environment	2.1 Understanding the current practices of the collaborating company of selecting different design tools and method in the preliminary phase using the RR- SBD process model 2.2 Analysing the industrial requirements to aid the selection of the suitable design tools and methods for the different activities to enhance the application of the SBD process model. 2.3 Analysing the detail of the capability of different design tools and methods against the captured requirements
3 SBD Navigator Logic	3.1 Attending design meetings to observe the way of thinking (logic) and decision making in preliminary design phase within the collaborative company 3.2 Developing logical guidelines to select the suitable design tools and methods for specific SBD activities within the preliminary design phase 3.3 Modifying RR-SBD process model for the implementation of the potential SBD Navigator

4 SBD Navigator's Software development	4.1 Defining the suitable software requirements in order to develop the computerised software to navigate SBD process model 4.2 Designing standard template(s) to describe different design tools and methods selection choices and the logic of its usage within SBD Navigator of the SBD process model in Rolls-Royce based on different project scenarios 4.3 Supporting the development of the SBD Navigator by editing the software code via online interface in order to modify the functionality and the layout that represents the difference stages of the RR-SBD process model
5 Validation	5.1 Validating the new RR-SBD process model using the SBD Navigator via research based use case study, and expert judgement.

Figure 1: Research Methodology

The following describes each phase and tasks within the research methodology in detail:

<u>Phase 1. Background Theory</u>

1.1 The extensive literature review of Product Development and SBD topics to understand the need for the improvement of the PD practices in SBD environment.

1.2 In order to enhance the existing SBD process model within the collaborating company their current SBD process model evolution has been examined. The opportunities of process improvements of the current process model have been analysed in order to understand the scope of the process improvement.

<u>Phase 2. SBD environment</u>

2.1 The selection of design tools and methods within the preliminary phase of the collaborating company using the RR-SBD process model has been analysed in order to enhance this selection by incorporating new research findings and best practice.

2.2 Analysis of the industrial requirements to aid the selection of the suitable design tools and methods for different PD activities to enhance the application of SBD process model has been examined.

2.3 Detail analysis of the capability of different design tools and methods against the captured requirements has enabled a view of the current RR-SBD process model from an analytical perspective. These findings allowed the evaluation of the customisation of the usage of the design tools and methods within Rolls-Royce plc. In certain cases of inappropriate usage of SBD tools and methods, suggestions of improvement based on best practice and research findings have been made.

Phase 3. SBD Navigator's Logic

3.1 Internal design meetings within the collaborating company have been attended to observe the way of thinking (logic) and decision making in order to understand possible SBD process improvement points.

3.2 Logical guidelines have been developed for the SBD Navigator to select suitable design tools and methods based on tasks 2.1, 2.3 and 3.1 for specific SBD practice within the Rolls- Royce plc preliminary design phase.

Phase 4. SBD Navigator's Software development

4.1 The software requirements have been specified in order to develop the SBD Navigator suitable for the collaborative company's IT environment in order to navigate through the enhanced RR-SBD process model.

4.2 Standard SBD Navigator templates have been designed to describe different design tools and methods selection choices/options and the logic of their usage within the RR- SBD process model based on different project scenarios.

4.3 The development of the SBD Navigator has been supported by editing the software code via online interface in order to modify the functionality and the layout that represents the different stages of the RR-SBD process model. An agile software development manner has been adopted allowing amendment of the code in a time efficient manner when needed.

Phase 5. Validation

5.1 The enhanced RR-SBD process model has been validated via the SBD Navigator, which has incorporated altered design tools and methods selection. A low noise engine case study has been presented to potential users for evaluation and feedback. An expert from Rolls-Royce plc has helped to analyse and translate the feedback into the second iteration SBD Navigator application requirements.

2. LITERATURE REVIEW

2.1 Overview of Product Development

New product development (NPD) is an important commitment in manufacturing companies. It is an interdisciplinary and creative activity to ensure that the company offers a wide variety of products in order to satisfy customer demands (Krishnapillai and Zeid, 2006). NPD involves important activities such as product specification, product design and engineering, production planning, manufacturing and assembly, as well as purchasing and commercialisation, as shown in Figure 2. Conceptual design in engineering is the most important act of the product lifecycle as up to 80% of the cost is determined in this activity (Boothroyd, 2010).

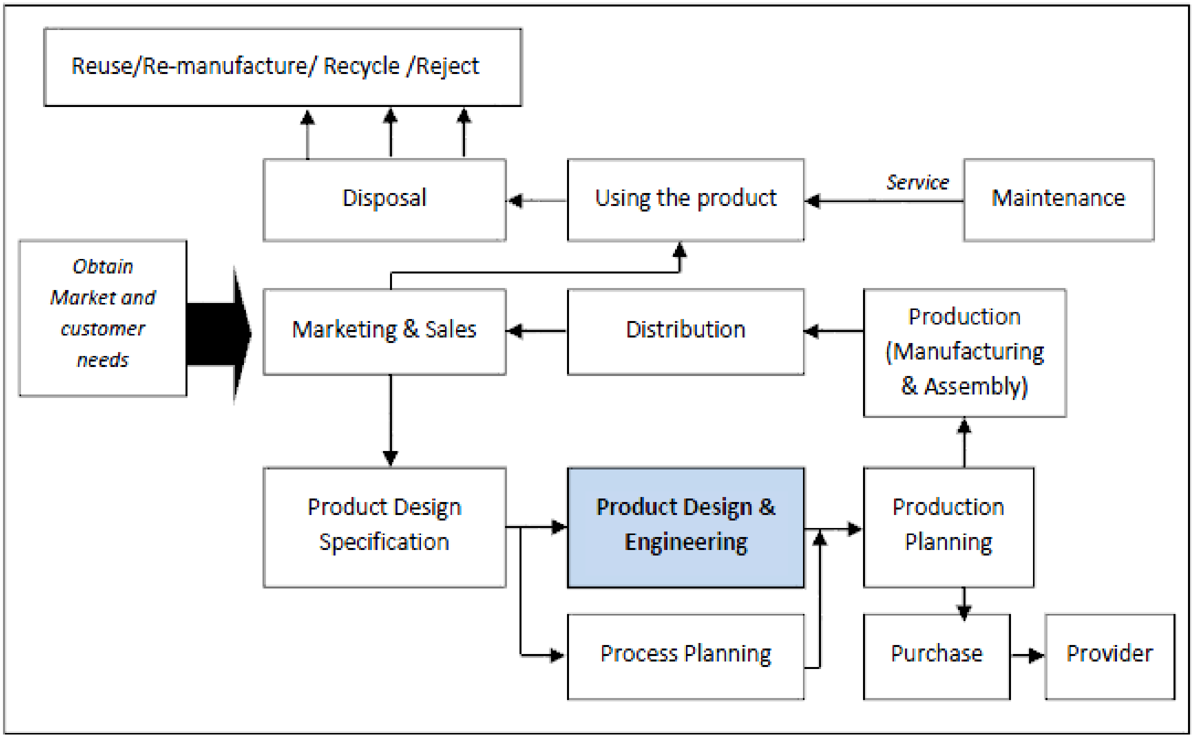

Figure 2: Product Development Cycle (Al-Ashaab, 2014)

The manufacturing company that fails to make correct decisions in the initial phase will increase of the life-cycle cost in product development by up to 75%-80% (McCarthy et al., 2006; Mileham et al., 1993). Thus, the activities in NPD are critical and will provide continuous support to manufacturing companies, involving all divisions, processes and tools. However, determining the core processes in product development and defining the relationship to the company's capability are vital for sustainable success in developing a new product (Liu, 2003).

2.2 Lean Thinking Principles

Lean thinking is management philosophy derived mostly from the Toyota Production System (TPS). It is the practice that considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination. Value is any action, process or service that a customer would be willing to pay for (Al-Ashaab, 2013). The originality of lean thinking starts on the shop-floor of Japanese manufacturers and imposes domestic competition in Japan mainly for car makers. From the 1950s to the 1970s, Toyota completely applied lean to car manufacturing, vehicle assembly and the supply chain. After that, the 'hidden' secret behind Toyota was shared for the first time with other companies outside Japan. This opportunity was largely driven by western manufacturing to compete with Toyota's performance until the book entitled 'The Machine that Changed the World' highlighted the various gaps between western and Toyota performances (Womack et al,. 2007). They stated that the lack of contingency was the first criticism of lean in less efficient manufacturers. This is because manufacturers focus on lean on the shop-floor and rely on the five lean principles but not on lean integrative approaches. However, the key to the high performance of Toyota is the fact that they practice a continuous improvement and learning culture within their underlying lean principles (McManus et al., 2007).

The lean principles proposed by Womack et al. (2007) are highlighted as: (1) specify value; (2) identify the value stream and eliminate waste; (3) create the value flow; (4) let the customer pull the processes; and (5) pursue perfection. These principles are summarized in Womack and Jones' statement about 'lean thinking', i.e. that it "provides a way to specify value, line up value-creating actions in the best sequence, conduct these activities in the best sequence, conduct these activities without interruptions whenever someone requests them, and perform them more and more effectively" (Womack et al., 2007). All these principles are commonly applied to the shop-floor (or called lean manufacturing). The transformation of lean tools and techniques on companies' shop-floors has changed the landscape of the traditional environment. This transformation has allowed organizations to work more smartly with quantum improvements and has driven growth of the manufacturing companies with marginal benefits (Oosterwal, 2010). But to be more effective, and for manufacturing companies to be more efficient, lean thinking cannot stop at the shop-floor. The shop-floor constitutes only one chapter in lean thinking and companies almost never form a true learning culture in their process – lean manufacturing and lean enterprise represent limited and piecemeal approaches (Liker and Morgan, 2006).

Khan et al (2013) believe that there are five core enablers for Lean PD:
(1) SBCE process; (2) Chief engineer (entrepreneurial) technical leadership; (3) Value-focused planning and development – this includes customer value, profit, amongst other attributes; (4) Knowledge-based environment; (5) Continuous improvement culture.

2.2.2 Introduction to Set-Based Concurrent Engineering / Set-Based design

The theoretical underpinning for Set-Based Concurrent Engineering (SBCE) is likely to be the natural progression of product design and development, although it has also been attributed to Japanese manufacturers (Ward et al., 2014). The notion to explore a set of alternative solutions before taking them through a structured evaluation process is common in engineering textbooks (Ulrich and Eppinger, 2000). SBCE and SBD are interchangeable process models; however SBD focuses mainly on the early preliminary design phase, while SBCE refers to the whole cycle of product development including the introduction of the product to the market. Figure 3 represents the evolution of the SBCE process model.

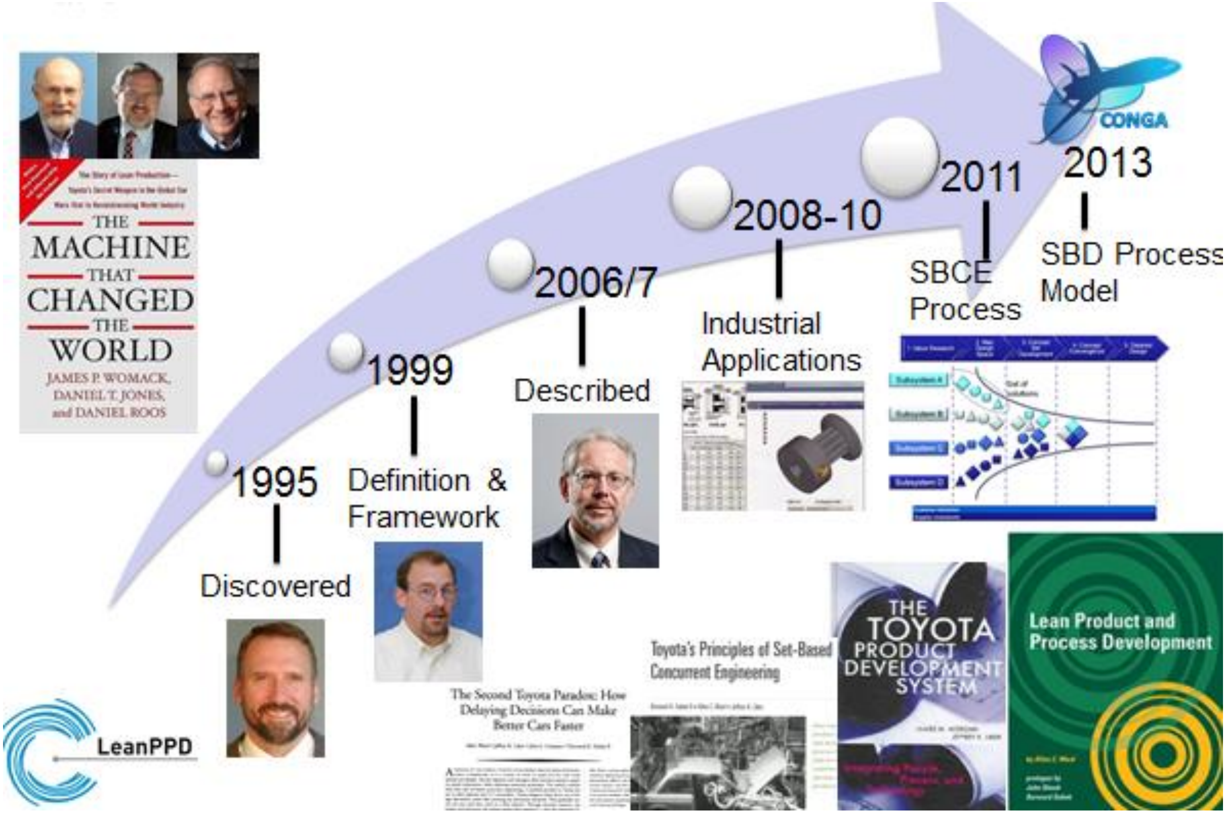

Figure 3: The Evolution of SBCE / SBD (Al-Ashaab, 2014)

In 1995 Ward analyzed why Japanese manufacturers were more successful compared to the American industrial rivals: he discovered that the real success was the Toyota PD system rather than their production system. Sobek, who was doing a PhD (1999), under Ward's supervision, started to define the principles and the framework of the SBCE process model based on their understanding of Toyota's PD. Later on, Liker and Morgan (2006-2007) described the detail principles of Toyota's PD system. Shortly, several industrial applications followed (2008-2011), that established main ideas of the new approach. However, none of this work gave a detailed description and a systematic approach of defining SBCE process model. In between 2009-2013 the Lean PPD team at Cranfield put forward a detailed description of a process model and the associated toolset (Khan 2012, and Al-Ashaab 2013). Further steps to progress this process model were taken in the CONGA development project which defined a simplified version of the SBD process model suitable for the industrial collaborative environment. In concurrent engineering, PD activities that previously took place sequentially should be conducted in parallel so that design, manufacturing, and other functions are better integrated. The primary objectives are essentially to reduce the lead time required to bring a new product to the market, and to facilitate the consideration of many aspects of a product's lifecycle early in the design process. Although the objectives of concurrent engineering are logical, there is no single approach to achieve them. Concurrent engineering research has focused on supporting socio-organizational mechanisms with special emphasis on communication (Khan, 2012). SBCE/SBD approach aims to create high innovation design possibilities with low risk benefits.

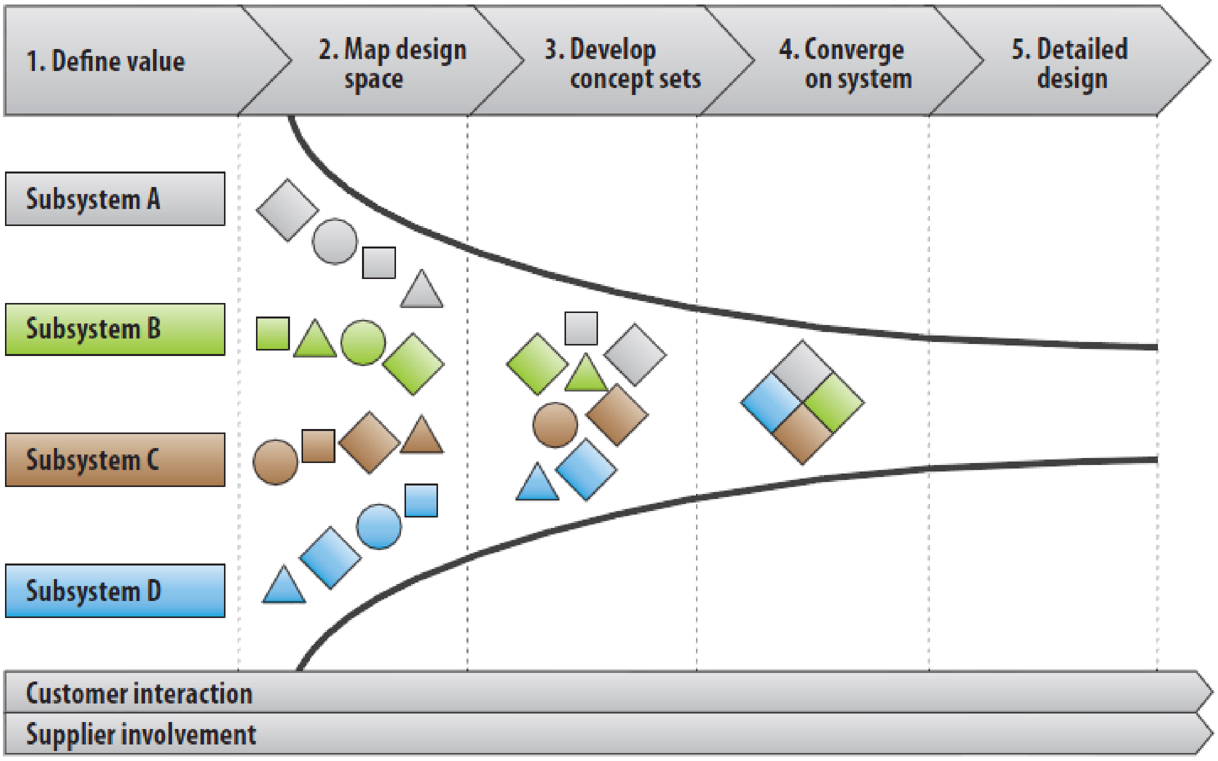

Figure 4: SBCE/SBD baseline model (Khan, 2012)

In SBCE/SBD participants carry out product development and design activities by developing and exchanging the design information regarding sets of design solutions in parallel, as shown in Figure 4. As the design matures, participants gradually narrow their respective sets of solutions based on the knowledge gained from various activities like stimulation, testing etc, committing to staying within the set that they can rely on. By that time there is strong evidence whether the solution can meet the requirements and which solution satisfies them the best. Critical design decisions are delayed on purpose in order to ensure that customer expectations are fully understood. By following SBD process, companies are able to explore high risk solutions in parallel with low-risk design solutions

(Ward and Sobek, 2014). Figure 5 shows the key principles of SBCE/SBD combined by Khan (2012).

A majority of PD experts agree that Lean PD principles need to be translated into a more effective process model that would help to implement the Lean PD process model, which core element is SBCE/SBD, within industrial companies: Liker and Morgan (2006) mention the complexity of human systems and technology, making the need for systematic perspectives more critical to the 'lean initiative' in product development. According to Ward and Sobek (2014) "Almost all defective projects (projects that miss the market, have manufacturing cost or quality problems, or budget and time overruns) result from not having the right knowledge in the right place at the right time. Therefore, re-useable knowledge is the basic value created during the development. Hoppman (2009) claims that shortcomings of existing approaches in the introduction of lean product development (Fiore, 2005; Kennedy et al., 2008; Liker and Morgan, 2006; Schulze and Störmer, 2012; Ward, 2007) are mainly due to the detailed definition of their process models.

1. **Strategic value research and alignment**
    a) Classify projects into a project portfolio
    b) Explore customer value for project x, Align each project with the company value strategy
    c) Translate customer value (product vision) to designers (via concept paper)
2. **Map the design space**
    a) Break the system down into subsystems and sub-subsystems
    b) Identify targets/essential characteristics for the system
    c) Decide on what subsystems/components you want to improve and to what level (selective innovation)
3. **Create and explore multiple concepts in parallel**
    a) Pull innovative concepts from R&D departments
    b) Explore trade-offs by designing multiple alternatives for subsystems/components
    c) Ensure many possible subsystem combinations to reduce the risk of failure
    d) Extensive prototyping (physical and parametrical) of alternatives to test for cost, quality, and performance
    e) Communicate sets of possibilities
4. **Integrate by intersection**
    a) Look for intersections of feasible sets, including compatibility and interdependencies between components
    b) Impose minimum constraint:
    c) Seek conceptual robustness against physical, market, and design variations
    d) Concurrent consideration of lean product design and lean manufacturing
5. **Establish feasibility before commitment**
    a) Narrow sets gradually while increasing detail: functions narrow their respective sets in parallel based on knowledge gained from analysis (all)
    b) Stay within sets once committed and avoid changes that expand the set
    c) Control by managing uncertainty at process gates

Figure 5: Adapted from principles of Set-Based Concurrent Engineering (Khan, 2012)

The SBCE/SBD principles in Figure 5 were used to develop a detail SBCE process model shown in Figure 6 (Khan, 2013).

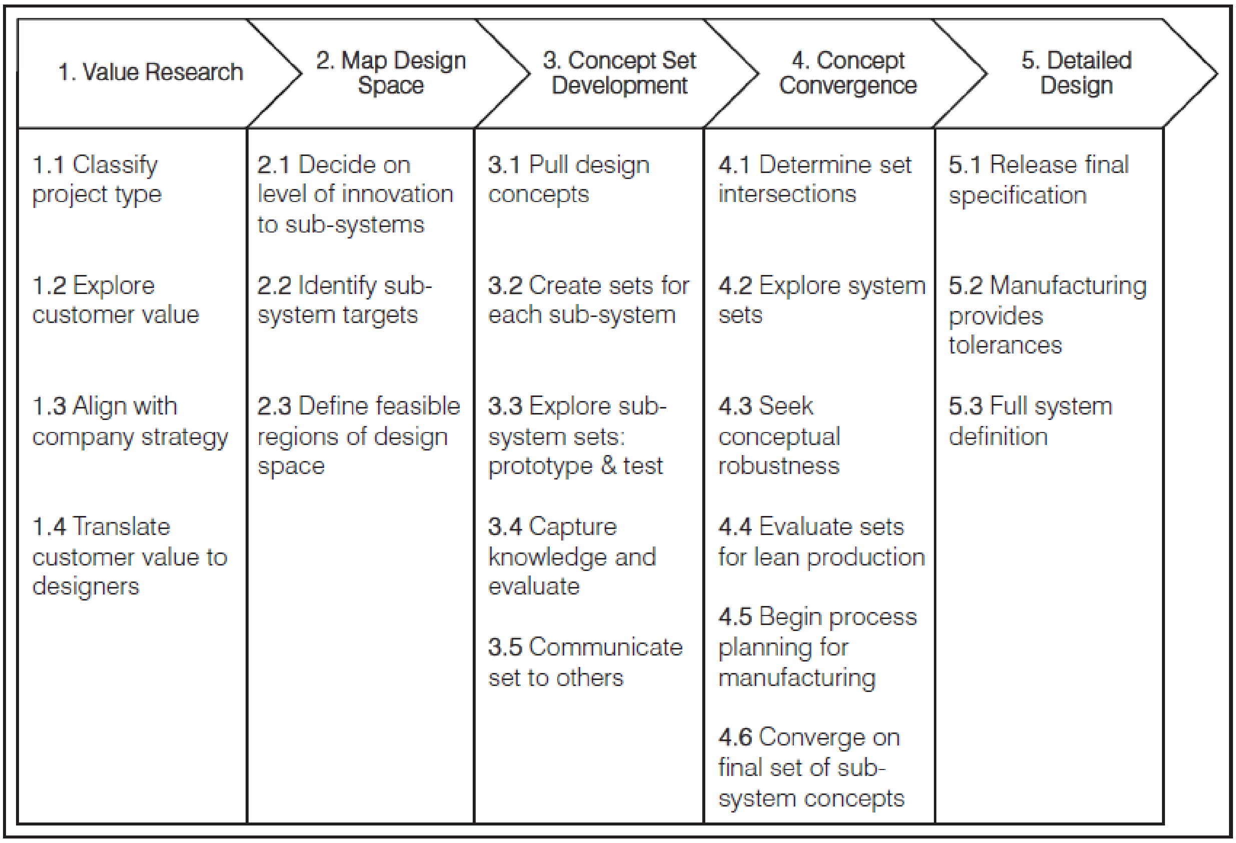

Figure 6: SBCE/SBD process model activities view (Khan et al, 2012)

The main outcomes of the five SBCE process model phases can be summarised as follows: 1. Value research: the project is classified and defined according to the level of innovation incorporated. The customer value would also be identified in order to evaluate the 'leanness' of the design alternatives and align the project with the company strategy. 2. Map design space: design participants or subsystem teams define the scope of the design work required, as well as the feasible design options/regions. This includes deciding on the level of innovation of the system and sub-systems. 3. Concept set development: each participant or subsystem team develops and tests a set of possible conceptual sub-system design solutions. Work at this stage includes exploring sub-system sets, such as simulation, prototyping and testing. Knowledge created during these activities is captured and utilised to evaluate different sets of solutions. Sets of solutions are communicated within teams to receive feedback and understand constraints. 4. Concept convergence: sub-system intersections are explored, and integrated systems are tested. Based on the knowledge produced in this phase, the weaker system alternatives will be purged,

allowing a final optimum product design solution to enter the final phase. Elimination takes place in the light of several activities, including evaluating robustness, assessing costs and gradually converging towards a solution. 5. Detailed design: the final set is concluded and final detailed specifications are released (Khan, 2012).
The described SBCE model has been used in this research to support the enhancement of the PD model within the collaborative company which is presented in chapter 3.

2.3 Overview of product development tools and methods

This section presents a brief overview of the typical design tools and methods that have been used in traditional product deveopment process models. The author divides them into documentation methods, decision methods, design methods, value analysis and problem solving methods. This classicication is based on understanding the capabilities of each tool and method as well as the functions they provide to support different activities at different design stages within a typical product development process model.

DOCUMENTATION

Customer Requirements Document – a document that contains particular needs of a customer in a uniquely identifiable statement, which can be validated and against which a solution can be verified (Lutters et al, 2014).

Systemic Textual Analysis - is concerned with the analysis of expressed customer requirements with the purpose of interpreting, expanding and clarifying and identifying missing requirements. It uses a systems approach through the consideration of a Holistic Requirements Model to help identify deficiencies and omissions in the source requirements (Burge and Walsh, 2015).

Product Definition Document – a document that shows the process of producing a product design, the aim is to make sure that the development and the intended new product match the needs of the customer/user (Burge and Walsh, 2015).

Product Development Strategy Matrix – a tool to identify strategic benefits that can be sought from projects (Khan 2012).

Quality Function Deployment (QFD) - aids the translation of vague, imprecise Customer Requirements into clear measurable Technical Requirements. Based upon a sequence of matrix charts, QFD provides a logical and systematic methodology for capturing and organizing the requirements translations necessary for effective and efficient new system introduction (Burge and Walsh, 2015).

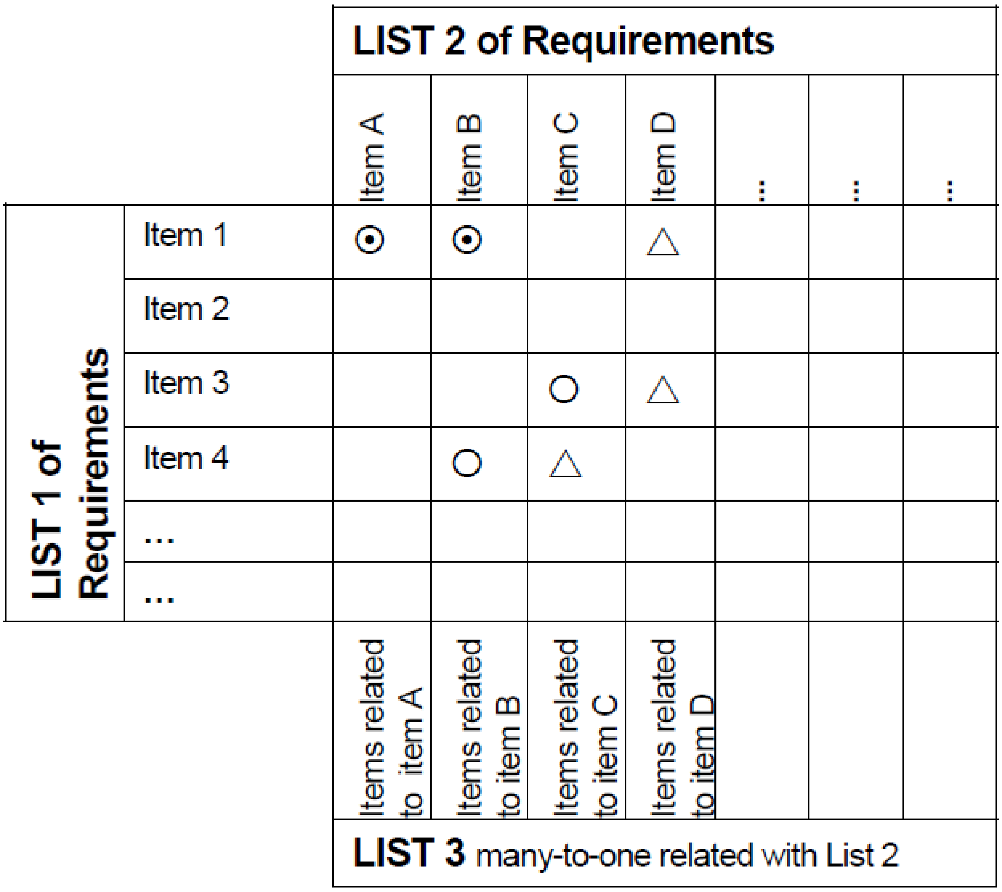

Figure 7: Basic structure of QFD matrix diagram (Burge and Walsh, 2015)

Viewpoint Analysis - is a tool that allows the team to identify, structure and document the requirements of a system. The outcome is a *Viewpoint Structure Chart.* This chart, Figure 8 - presents a hierarchical decomposition of the system functionality that has been identified as necessary to meet the prime systems operational requirements together with the external functionality of the wider system of interest (Burge and Walsh 2015).

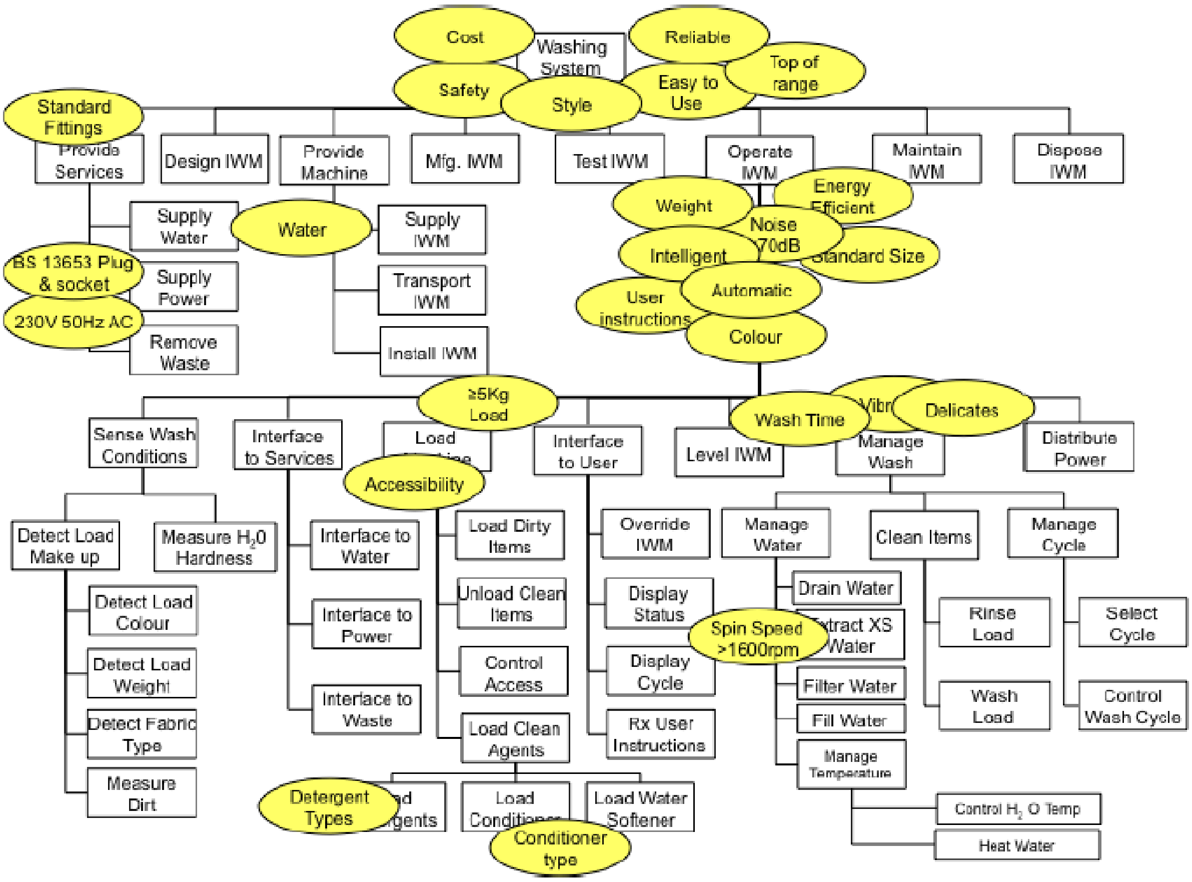

Figure 8: An example of Viewpoint Analysis (Burge and Walsh, 2015)

DECISION METHODS

<u>Matrix Decision Analysis</u> - is a tool that allows a team to identify the presence and strengths of relationships between two or more lists of items. It provides a compact way of representing many-to-many relationships of varying strengths (Burge and Walsh, 2015).

		List 2				
		Item A	Item B	Item C	Item D	Item E
List 1	Item 1	⊙	⊙		△	
	Item 2					
	Item 3			○	△	
	Item 4		○	△		
	Item 5	△		△		○
	Item 6		○		⊙	

Figure 9: An example of a Matrix Diagram (Burge and Walsh, 2015)

Function Means Analysis - is a highly structured approach to generating, selecting and documenting system design concepts. The resulting table is used to show all potential design options simultaneously, making it easier to apply selection/de-selection criteria to help generate whole system concept solutions (Burge and Walsh, 2015).

FUNCTION – MEANS ANALYSIS CHART							
System: Intelligent Dish Washer	Sub-System		Date: 1 April	Author: S Clean		Issue: 1.0	Revi
FUNCTION	MEANS						
Detect Load Make Up	Bar coded Items	Vision recognition	Infra red camera and recognition	Ultrasound	Electronic Tags	User defined	Mass Spectroscopy
Measure Water Hardness	Hardness sensor	Installation defined	User defined				
Load Dirty Items	Bottom Hinge Door	Slide door Hinge	Top Door	2 Sliding Baskets	Conveyor		
Unload Cleaned Items	Bottom Hinge Door	Slide door Hinge	Top Door	2 Sliding Baskets	Conveyor		
Load Cleaning Agents	Pull out tray	In-door compartment	In-door Hopper	In machine body Hopper	No cleaning agents		

Figure 10: An example of functional means analysis (Kumar and Phrommathed, 2005)

SWOT Analysis - the analysis of strengths, weaknesses, opportunities, and threats is widely used to compare and contrast two or more entities. The tool covers not only strengths and weaknesses, which are the internal attributes of the compared items but also such external characteristics as opportunities that might add into their strengths and threats that may turn into weaknesses (Kumar and Phrommathed, 2005).

Pugh Matrix - is a type of Matrix Diagram that allows for the comparison of a number of design candidates leading ultimately to which best meets a set of criteria. It also permits a degree of qualitative optimisation of the alternative concepts through the generation of hybrid candidates. The Pugh Matrix is easy to use and relies upon a series of pairwise comparisons between design candidates against a number of criteria or requirements. One of its key advantages over other decision-making tools such as the Decision Matrix is its ability to handle a large number of decision criteria (Pugh, 1996).

	Design Concept A	Design Concept B	Design Concept C	Design Concept D	Design Concept BC	Design Concept BD
Criteria 1	S	+	S	+	+	+
Criteria 2	S	-	S	+	S	+
Criteria 3	S	S	S	+	S	+
Criteria 4	S	-	+	+	+	+
Criteria 5	S	-	+	+	+	+
Criteria 6	S	-	S	-	S	-
Criteria 7	S	+	S	-	+	+
Criteria 8	S	+	S	-	+	+
Criteria 9	S	-	S	-	S	-
Criteria 10	S	S	-	S	S	S
TOTAL +	0	3	2	5	5	7
TOTAL -	0	5	1	4	0	2
TOTAL SCORE	0	-2	1	1	5	5

Figure 11: An example of completed Pugh matrix (Burge and Walsh, 2015)

Concept Intersection Matrix – evaluates integration between sets of subsystems or component alternatives, it uses a traffic light colour coding approach; green indicates that two components or subsystems are easy to integrate, amber indicates that there is likely to be some conflict, and red indicates that the two do not integrate (Khan, 2012).

DESIGN METHODS

Formal Brainstorming Session – idea generation technique (Khan, 2012)

Taguchi Robust Design Methods (e.g. P-diagrams) - (parameter diagram) elegantly captures the factors that may cause variation in performance (Burge and Walsh, 2015).

Design-FMEA – is an application of the failure mode and effect analysis method to product or service design (Lutters et al, 2014).

Process FMEA - is a structured approach that assigns quality risk levels to each step in a process (manufacturing or transactional). It is a powerful *prevention tool*, since it does not wait for defects to occur, but rather anticipates them and implements countermeasures ahead of time (DMAIC Tools, 2015).

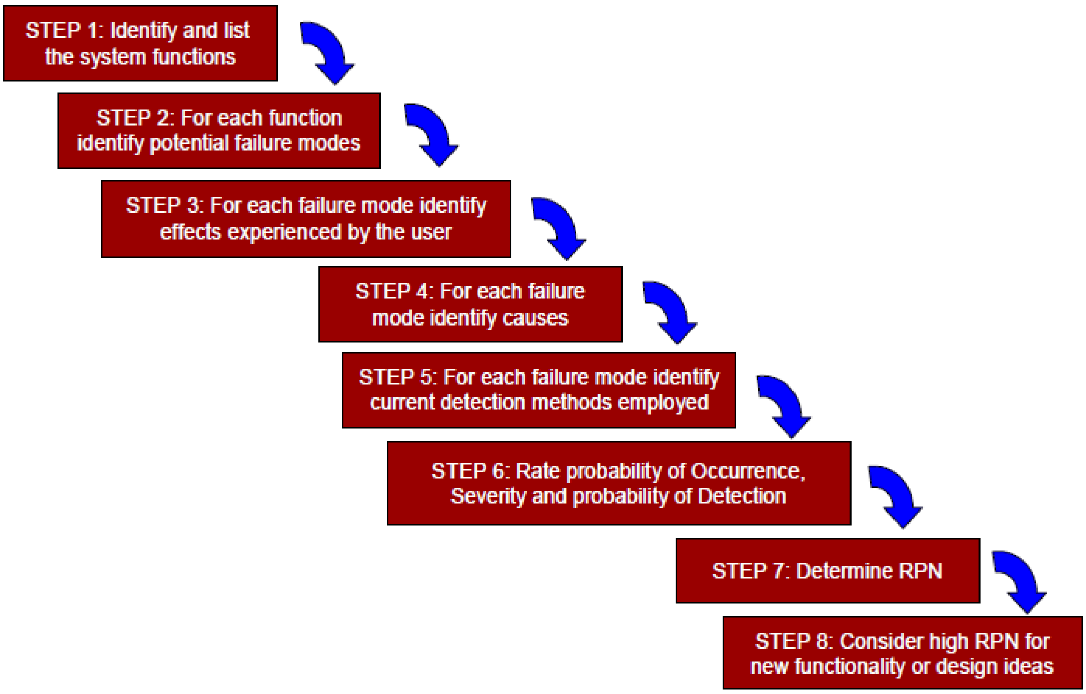

Figure 12: Basic FFMEA process (Burge and Walsh, 2015)

Functional Modelling - is a tool that allows a team or an individual to produce a behavioural/operational model of an existing or planned system. The resulting model shows the system functionality and the logical interconnections between that functionality (Burge and Walsh, 2015).

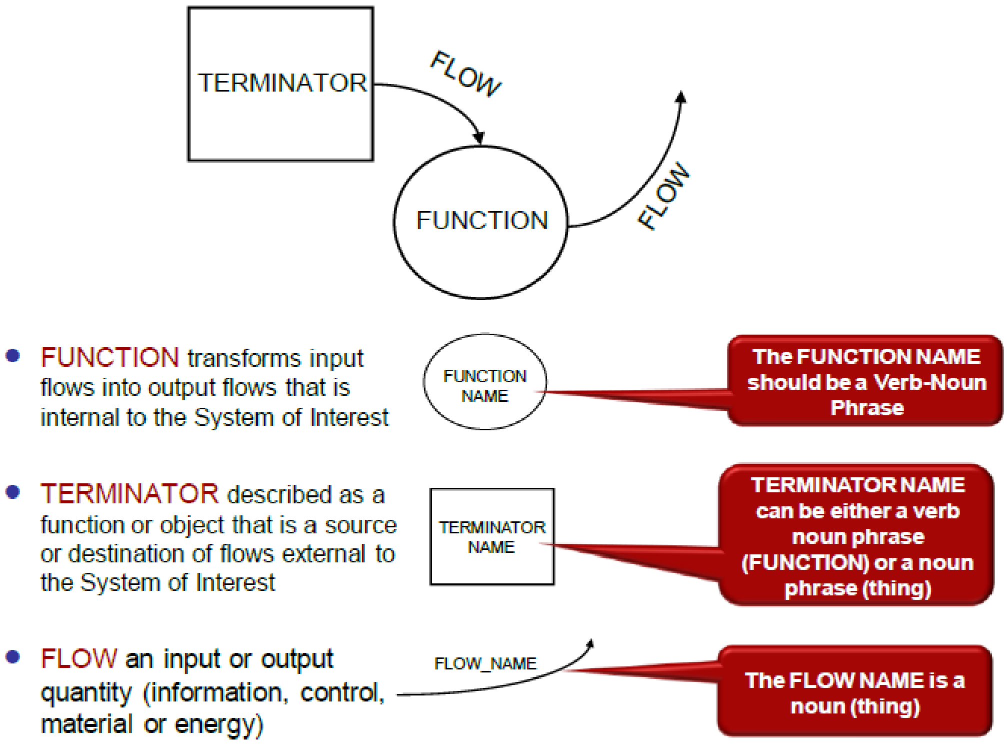

Figure 13: Functional modelling (Burge and Walsh, 2015)

Need Means Analysis - is a systems thinking tool aimed at exploring alternative system solutions at different levels in order to help define the boundary of the system of interest. It is based around identifying the "need" that a system satisfies and using this to investigate alternative solutions at levels higher, the same and lower than the system of interest (Burge and Walsh, 2015).

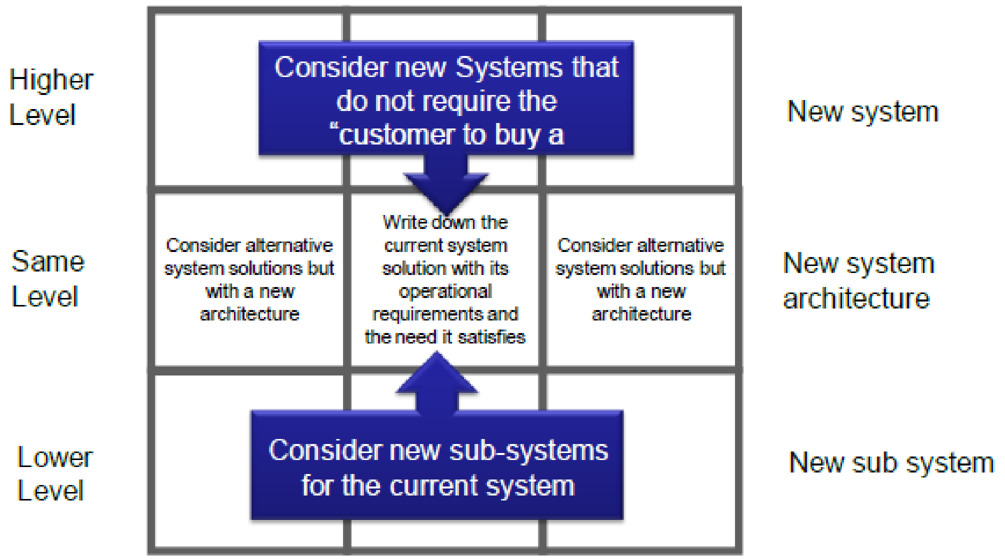

Figure 14: Need means analysis 'box of nine' (Burge and Walsh, 2015)

<u>Design of Experiments</u> - is used for systematically exploring the design space available in order to understand the key parameters that drive the performance characteristic in which you are interested. It can 'screen out' those factors that have negligible effects in order to simplify the problem, detect and quantify 'interactions' between control factors and determine a nominal design It also permits the building of fast-running 'surrogate models' of slow-running analysis codes to make practical a comprehensive search of the design space and use of robust optimisation techniques that require a large number of iterations of the analysis codes (Burge and Walsh, 2015).

<u>Context Diagrams</u> - is a component of Functional Modelling that stands on its own as a valuable tool. It allows a team or an individual to produce a high-level model of an existing or planned system that defines the boundary of the system of interest and its interactions with the critical elements in its environment. A Context Diagram is a single picture that has the system of interest at the centre, with no details of its interior structure or function, surrounded by those elements in its environment with which it interacts (Burge and Walsh, 2015).

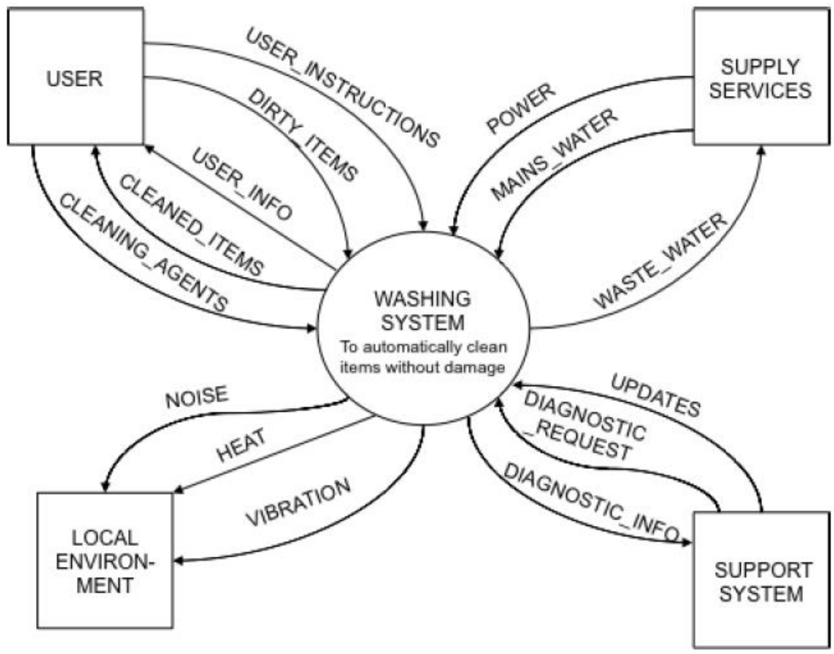

Figure 15: An example of Context diagram (Burge and Walsh, 2015)

VALUE ANALYSIS

<u>Analytic Hierarchy Process (AHP)</u> - is a mathematical way to determine the importance of each key non-functional requirement such as:

- Cost
- Lead time
- Technical Performance
- Design risks
- Safety improvement, etc.

The primary role of the AHP is to indicate which is the best direction to drive the design towards (Burge and Walsh, 2015).

<u>Product Value Map</u> – a simple technique that brings together customer (product) value attributes. It structures a project into main 5 categories: general functional, product/sector specific, service and support, psyhological/sensory and other necessary attributes (Khan, 2012).

Functional Flow Diagrams – is a time sequenced, step by step flow diagram that displays the system's functional flow and is usually very simple, allowing focus on the system rather than on a modelling technique (Burge and Walsh, 2015).

PROBELM SOLVING TOOLS

TRIZ (Theory of Inventive Problem Solving) – helps to generate better ideas, it is a set of tools which help to understand the problem and identify the resources which may be able to solve the problem (Burge and Walsh, 2015).

A3 Report (single A3 paper size report) - a technique for problem solving in product design for knowledge capture and sharing and the generation of the process using the A3 thinking approach for effective implementation. It provides useful knowledge as a design reference to generate decision making at the initial stages of product development and helps designers to prevent recurrence of the same problem, eliminating design mistakes and enhancing design decision (Saad, 2013).

5 Why Analysis - a tool that enables the identification of the root cause of the problem by asking 'Why' 5 times, it allows to understand the root cause problem deeply enough to solve (Khan, 2012).

Fishbone Cause & Effect Diagram (Ishikawa) – as the purpose of the diagram is to delineate all possible causes of the problem, it is preferable to obtain the point of view of several individuals who know the process. It is most often developed as a group activity during the brainstorming sessions (Burge and Walsh, 2015).

2.3.1 Review of the related work of selecting PD tools and methods

This section presents an overview of the research work related to selecting different tools and methods to support PD projects.

The main idea of the research reported by Sales de Araujo (2001) is to have a clear understanding of the nature of the phenomenon of PD tools acquisition as an essential step before being able to develop a recommendation to support this activity in practice. The key elements that influence the tool acquisitions are: 1) the practitioner (the user of the tool in the company), 2) the marketer (the company who make and sell the tool), 3) the acquisition process (technically the exchange process that connects tool user with the marketer), 4) the individual influence factors (psychological issue during the acquisition process, and 5) the environmental influences, which includes the large array of factors outside of the practitioner's control.

A 'Tool Selector' as a computerized guide, to support decision process of selecting PD tools, that has been translated into software code using MS Windows environment, was mentioned as early as 1997 (Thoben et al., 1997). It contained descriptions of more than 100 methods, techniques and tools to guide the designers and engineers from a specific PD problem to the solution. This tool selection methodology worked within concurrent engineering framework. The software tool selector intended to provide its user with a decision support for the selection of different PD tools (such as CAX-systems), techniques (e.g. quality audits) and formal tools (e.g. Design for Manufacturing and Assembly), based on individual company specific requirements. This research highlighted possible issues in typical PD tools selection process: managers' knowledge of certain design tools might have influenced the selection of them even when the usage of these tools was not optimized in any way. However the 'Tool Selector' methodology and software idea provided the end used with the opportunity to support their search for the set of solutions to be likely appropriate for their case.

The later research on PD tools and methods selection, that involved 75 companies found out that the following factors influence the adoption of NPD tools and techniques: 1) the involvement of senior management, 2) the internal characteristics of organizational structure (e.g. company size, number of key department involves in NPD), 3) the external characteristics of the organization and 4) innovation level (Nijssen and Frambach 2000).

Buyukozkan et al, 2004 stated that several product development activities are repetitive, non-creative or routine activities which could be done by the individual without the need of the collaborative effort or design tools to be used while others require intelligence to support decision making. They classified PD tools and techniques into:

1- Networking e.g. emails, groupware and multimedia to support concurrent engineering collaboration.
2- Management tools such as data managements that include PDM, PLM, ERP.

3- Modelling and analysis tools such as CAD/CAM/CAE. This includes also the product data exchange standards such as STEP and IGES.
4- Predictive tools such as failure mode and effect analysis (FMEA), TRIZ, value engineering.
5- Intelligent tools such as knowledge based engineering software, artificial intelligence work.

The emphasis in this case was put on the suitable implementation of the mentioned design tools by combining their usage with the right resource allocation and sufficient personal training to make them effective in supporting PD.

This type of the classification was also used by Anand and Kodali (2008). They emphasized that a company could not achieve Lean PD implementation by only implementing PD tools and techniques. They underlined the importance of having a framework or a process model to guide PD project teams through how these different tools and methods should be used in order to enable different activities. Furthermore, they also provided a framework for how different design tools and methods could be used to eliminate or reduce waste in different PD activities.

2.3.2 Overview of SBD PD tools and methods

Figure 16 presents a view of the best practice compiled by the author adapted from the research findings of Khan (2012), of recommended tools and methods to be used to support different activities of SBCE/SBD. Research carried out by Khan (2012) on Lean PD models presents design tools, recommended for the Lean PD activity, classification. It describes most common existing industrial design tools as well as bespoke design tools, created to fill in gaps of design activities within the businesses: 'These tools were amalgamated from three sources: (1) identified Lean PD enabler; (2) practice at industrial collaborator companies; and (3) new tools developed to support the Lean PD model. Representatives from industrial partner companies asserted their preference for the tools that their employees were already familiar with. Many of the tools from the Lean PD enablers list are the standard engineering tools and are commonly used in industry. The representatives from industrial partner companies were, however, receptive to new tools that would provide significant benefit.'

These research findings confirm that a broad range of standard PD tools and methods are being widely used among industrial companies. However, it also highlights the need for creating bespoke techniques in certain cases in order to achieve Lean PD and SBD goals and to develop guidelines how to best adapt/apply them in design activities. The author of this research has analyzed design tools and methods that best enable SBCE/SBD and then compared the results with the current processes at Rolls-Royce by producing a table that incorporates commonly used tools and methods within industrial companies as well as bespoke solutions designed to solve particular design problems.

	Recommended tools for the SBD product development activities	SBD product development process model activities																	
		1.1 Classify project type	1.2 Explore customer value	1.3 Align with company strategy	1.4 Translate value to designers	2.1 Decide on level of innovation to subsystems	2.2 Identify subsystem targets	2.3 Define feasible regions of design space	3.1 Extract design concepts	3.2 Create sets for sub-systems	3.3 Explore subsystem sets	3.4 Capture knowledge and evaluate	3.5 Communicate sets to others	4.1 Determine intersections of sets	4.2 Explore possible product system designs	4.3 Seek conceptual robustness	4.4 Evaluate possible systems for lean production	4.5 Begin process planning for manufacturing	4.6 Converge on final system
PD tools enabling SBD (research and industry based)	Design concept matrix								■			■	■			■	■	■	■
	Design concept document (product definition)				■														
	Digital engineering (CAD/CAM/CAE etc)									■	■				■				■
	QFD		■		■		■												
	Trade-off curves											■	■		■				■
	Matrix decision analysis											■	■		■				■
	SWOT analysis											■							
	Know-how database (PDM/PLM)								■					■					
	A-3 single-sheet reports												■						■
	Market research tools		■																
	Stakeholder analysis			■															
	Requirements management software (DOORs)		■		■		■												
	Requirements document		■		■														
	Systemic textual analysis		■																
	Product value map		■																
	Lessons learnt logs							■											
	Best practice guides							■						■					
	Functional means analysis								■				■		■				■
	Need means analysis								■				■		■				■
	P-diagram														■				■
	Design of experiment														■				
	Functional flow analysis				■														
	Idea generation tools (Brainstorming)				■	■	■												
	Fishbone cause & effect diagram				■	■	■			■									
	Innovation frameworks (TRIZ)									■									
	DFMEA/FMEA															■			
	Modelling and simulation software															■			
	Context diagram						■	■											
	5 why analysis						■	■							■				
	Risk analysis																		■
	Analytical hierarchy process (AHP)																		■
	Pugh matrix																		■
	Viewpoint analysis																		■
	Design for manufacture and assembly (DFM/DFA)																	■	
Additional tools developed for the lean PD model	Project classification matrix	■																	
	Customer value model		■																
	PD strategy matrix			■															
	Innovation classification diagrams	■				■													
	Knowledge creation plan										■				■				
	Concept intersection matrix													■	■				
	Manufacturing and assembly process webs																	■	

Figure 16: Adapted from Khan (2012), recommended tools and methods to be used to support different activities of SBCE/SBD.

Khan (2012) discovered the need for developing bespoke tools to enable an effective implementation of the SBCE/SBD principles at certain design maturity levels. It is very important to acknowledge the growing complexity of the product structure and functionality which demands for more complex tools to be developed in order to address the possible design issues. Some of bespoke tools are shown at the bottom of the list of Figure 16. The following paragraph describes some of these tools.

Project Classification Matrix - maps projects against a number of project parameters. The matrix includes the project name (which ideally follows a standard format), scheduling information, the level of innovation, intended market, resource and cost data, and any other critical information deemed necessary.

Innovation Classification Diagrams – adopts the 'level of innovation' numbering scheme employed in the project classification matrix. The levels are colour-coded, and subsystems and components may subsequently be labelled to visually communicate the planned focus for innovation efforts in a particular project.

Product Value Model - simple representation that was developed to bring together customer (or product) value attributes. This product value model structures customer/product value attributes for a particular project into five categories: (1) general functional, (2) product/sector-specific, (3) service and support, (4) psychological/sensory, and (5) other necessary attributes.

Product Development Strategy Matrix - to identify strategic benefits that can be sought from projects. The produced matrix structures strategic goals around four categories: (1) knowledge, (2) organisation, (3) capability, and (4) creativity.

Knowledge Creation Plan - in order to focus concept testing activities on creating representations of knowledge that would support decision making, a document template was proposed. A knowledge creation plan could be produced for each system, subsystem, or component in order to ensure that the knowledge created enables weak solutions to be exposed, and increase confidence in the prominent design solutions.

Concept Intersection Matrix – evaluates integration between sets of subsystem or component alternatives. The matrix adopts a traffic light colour coding approach in which green indicates that two components or subsystems are easy to integrate, amber indicates that there is likely to be some conflict, and red indicates that the two do not integrate. The selection of colours is based on knowledge from previous projects and actually analysing or testing combinations. The results from this activity help to filter the sets of solutions in order to formulate system combinations.

Manufacturing and Assembly Process Webs - a simple visual representation to understand the available manufacturing and assembly process options for a number of system combinations.

The majority of these tools have been tested in an industrial environment. However, the knowledge Creation Plan has not been progressed beyond the research phase yet.

2.4. Research Gaps

The following are the key research gaps that have been drawn from the literature review and the analysis of the related literature:

RG1 Previous LeanPPD/SBCE research review highlighted the importance of using the right design tools and methods to enable effective completion of PD activities. However there is still a gap of what tools and methods should be used for a particular design scenario and at the specific activity of the SBD process model.

RG2 The selection of PD design tools and methods in SBD environment is mainly based on the tacit knowledge of designers and engineers at industrial companies. The lack of this methodology needs to be addressed by incorporating research findings and best practice from collaborating companies by capturing the tacit knowledge and converting it into the explicit practice.

RG3 There is a need to translate the enhanced SBD process model into a simplified version, which could be translated into the IT software that would guide potential users through the enhanced process steps while advising of the most suitable design tools and methods for each design activity.

3. ROLLS-ROYCE-SET BASED DESIGN PROCESS MODEL OVERVIEW

3.1 Rolls-Royce System Design Integration alignment to LeanPPD/SBCE principles

In 2011, Cranfield LeanPPD team introduced Lean PD principles to Rolls-Royce and proposed changes needed to apply SBCE/SBD perception on SDI (System Design Integration) processes. SBD refers mainly to the preliminary design phase while SBCE covers the whole design cycle up to the introduction of the product; hence this section refers to a broader perception of developing sets of solutions in parallel, shown in Figure 17.

RR-SBCE process model incorporates SBCE principles defined by the LeanPPD model (Khan et al., 2011). It is based on the integration of the principles and the good practice of the SBCE into the SDI process model, which covers the whole design cycle of the engine (product). It is divided into three levels: system level, sub-system level and component level. Defined sets of activities within the design cycles need to be performed in order to generate the document which is reviewed at the design review meeting at the end of the design cycle (SDR0, SDR1, etc.). Three main areas of improvement were identified as required in the SDI model:
Firstly, there was a need for a systematic definition of activities, and their associated tools and enablers, to generate a continuous flow of design knowledge throughout the process. Secondly, although the SDI model allowed for multiple system concepts to be generated, there was a tendency towards selecting a single solution at an early stage of the design process.
Finally, a considerable amount of rework was needed towards the later stages of development due to changing requirements related to development and certification. Such design changes required considerable resources. These three challenges were addressed by transforming the SDI model into the lean environment using SBCE principles, see Figure 5 to produce RR-Lean PD model. This process model was called RR-Lean PD model due to being developed in LeanPPD European project. The transformation process covered the first two design review stages of the system level - SDR0 and SDR1 (Al-Ashaab et al, 2013). SDR0 is concerned with top level system requirements, and it

aims to define the value by understanding what the system requirements are. SDR1 is concerned with system level specifications and making sure that initial system concepts meet such specifications (Al-Ashaab et al., 2013).

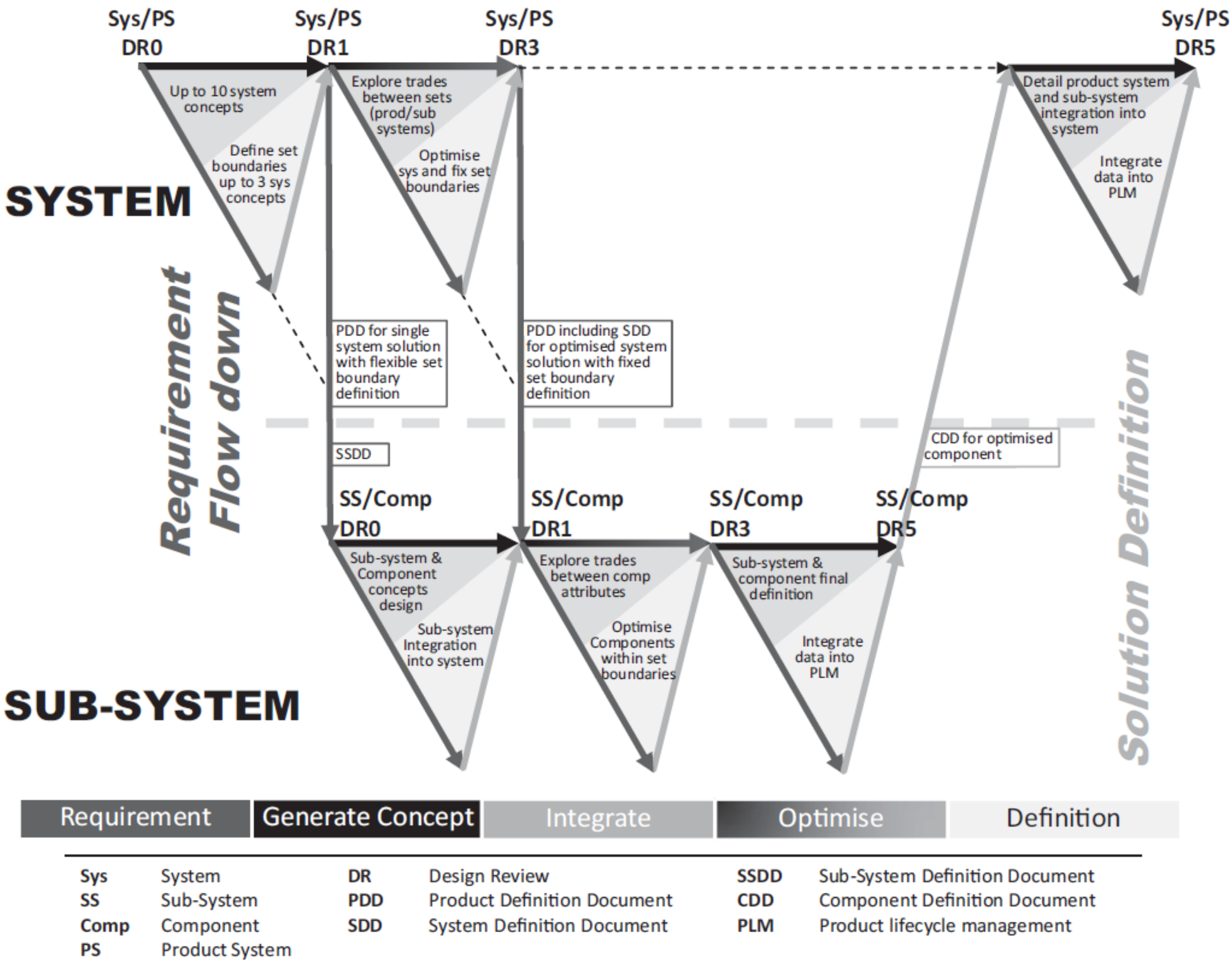

Figure 17: A simplified, two-level representation of the System Design Integration model (Rolls-Royce internal publication, 2012)

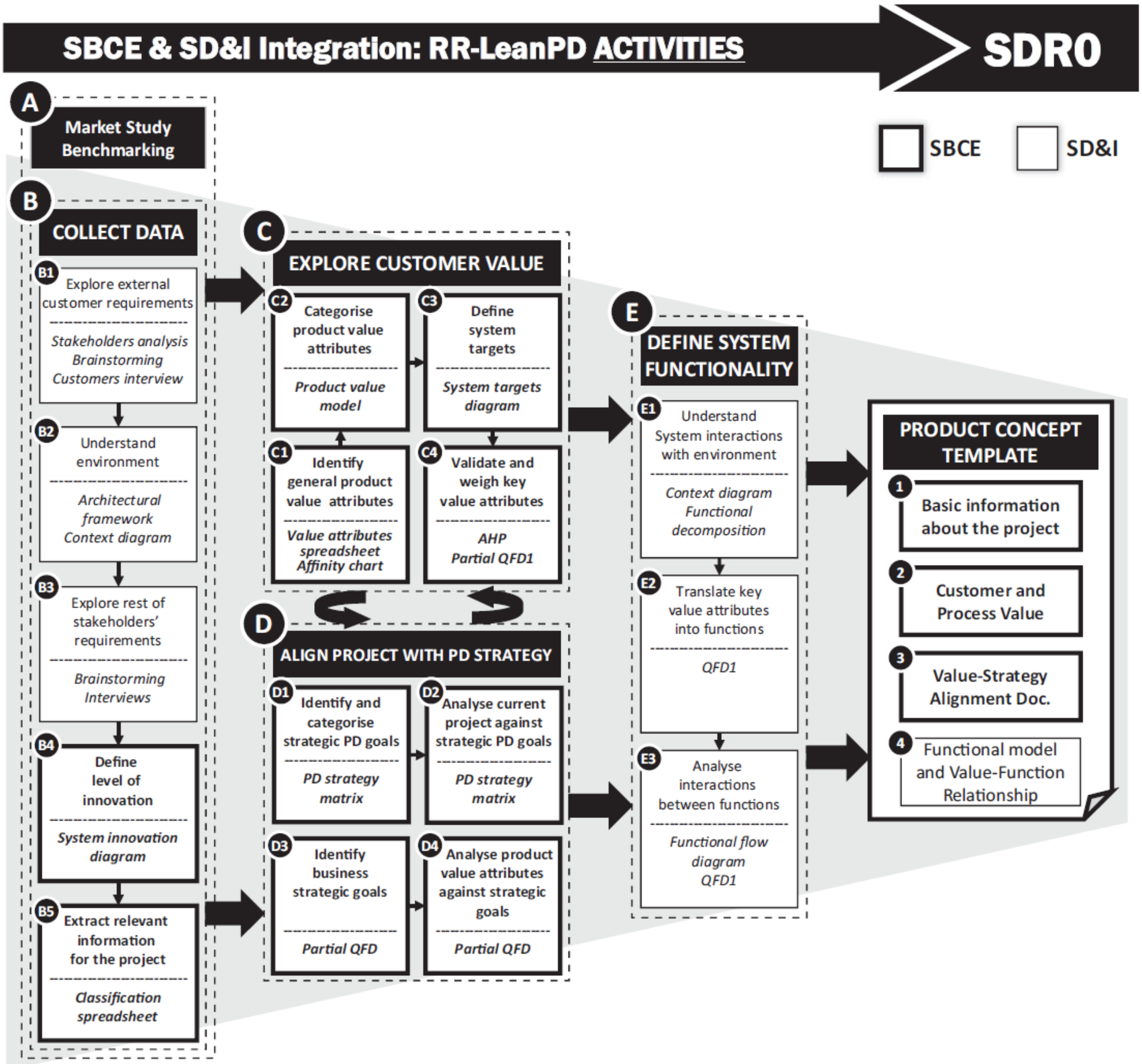

Figure 18: SBCE and SDI Integration process model SDR0 level (Al-Ashaab et al, 2013)

Figure 18 presents the activity view and matching tools of the RR-LeanPD model for SDR0. As illustrated by the bold coding of the squares, some activities and tools were kept from the original SDI, while others were integrated from the SBCE. Activities and corresponding tools were classified into five main groups, A–E, which corresponded to the first stage of the SBCE model '1. Define Value', and its four sub-activities (1.1–1.4) shown in Figure 6. The tool selection for the activities was based on the extensive literature review and the consultation of a few experts within Rolls-Royce to ensure that the tool would then enable the implementation of the SBCE principles. The following list outlines the activities in Figure 18. Activities A – market study and benchmarking. It aims to understand the market environment in which the project is located. Activities B – collect data. It aims to combine the knowledge necessary to make decisions about the set of solutions investigated and to enable familiarisation with the environment in which the product operates. It should be noted that sub-activities (B4) 'Define level of innovation' and (B5) 'Extract relevant information for the project' have been integrated into the SDI model because they represent two important elements in the SBCE paradigm. The first element is innovation, which is encouraged and fostered by exploring sets of design solutions at the system level rather than a single solution. The second is knowledge extraction, which is a crucial requirement for evaluating, communicating and eventually narrowing the alternative designs towards an optimum solution.

Activity C – exploring customer value. It corresponds to activity 1.2 in Figure 6 and aims to thoroughly understand the value of the customer, which is an important prerequisite for defining system targets and assessing the leanness of alternative designs. The value attributes are identified, categorised and weighted according to their impact in order to understand the importance of each attribute. Activity D – align project with PD strategy. It corresponds to the SBCE activity 1.3 'Align with company strategy' in Figure 6. It aims to define how the product will give the company new position in the market and increase its knowledge in relation to PD and responsibility towards the customer and the environment. Both Activities C and D are essential addition to the existing SDI model because they transform the PD process into a lean process in two ways: firstly, the customer value is thoroughly investigated and put at the centre of the PD process, and secondly, the key value attributes are aligned with the company's strategy. Both activities serve towards value creation, which is the essence of SBCE.

Activity E – defining system functionality. Activity E, which was already a part of the original SDI model, aims to transform the customer value from activity C into functions. The system's interactions with the environment are defined, and the key value attributes are translated into system functions. Finally, functions are analysed and assessed to understand the interactions between each other. The outcome of Activities A–E is documented in the Product Concept Template, which aims to thoroughly translate customer value to the design engineers. The 'Product Concept Template' was integrated in the new model because the original SDI model transferred the system design requirements via a requirements document, which did not ensure the explicit definition of customer value to different departments and functional groups. The Product Concept Template enforces the leanness of the PD process by centralising it around the customer value (Al-Ashaab et al, 2013).

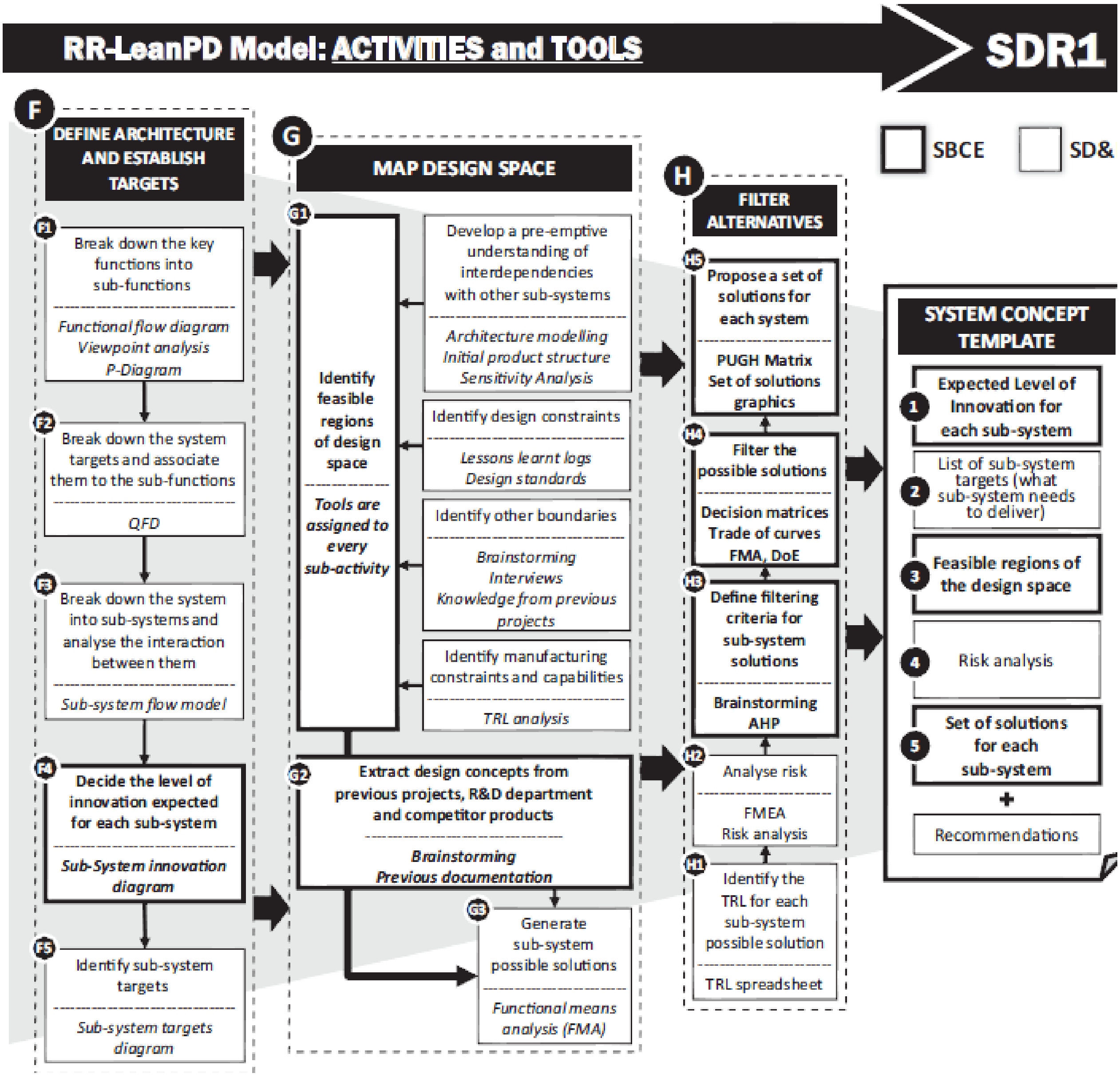

Figure 19: SBCE and SDI Integration process model SDR1 level (Al-Ashaab et al, 2013)

Figure 19 presents the activities and the toolset of the second PD stage of the RR-LeanPD model, which is the roadmap to SDR1. This stage of product design consists of three main activities, F–H. These activities correspond to SBCE activities 2 (map design space) and 3 (develop concept sets) in Figure 6. Activity F, 'define architecture and establish targets', starts at the point - where functional requirements were delivered from SDR0. This activity translates these functional requirements that were derived from the customer value into a set of targets. Activity F – defining architecture and establishing targets. It aims to break down the system (in terms of functions, targets and product architecture) and analyse the interactions between different sub-systems and its functions. Activity F4 is incorporated from the SBCE activity 2.1 shown in Figure 6, where the level of innovation of each sub-system is defined using an innovation diagram. As the level of innovation in subsystems increases, the number of solution sets is likely to increase. Finally, targets of different sub-systems are identified (activity F5) to ensure that the sets of design alternatives will satisfy the targets of all partners.

Activity G – map design space. Here, activities from both Stage 2 and Stage 3 of the SBCE model are incorporated, as shown in Figure 6. This is considered as a crucial stage for the success of the PD. This activity aims to identify the feasible regions of the design space (i.e. what can, may, should, must or must not be done) which corresponds to activity 2.3 in Figure 6 and to extract and develop alternative sub-system design solutions which correspond to activities 3.1 and 3.2 in Figure 6. Activity H – filtering alternatives. It is concerned with narrowing down the generated sets of solutions by filtering them based on the identified key value attributes, design capabilities and constraints, technology readiness level (TRL) and engineers' knowledge and experiences. Alternative sub-system solutions should be narrowed gradually, taking care not to freeze the designs early.

The last element of the RR-LeanPD model of the SDR1 aims to graphically present and communicate the set of alternative system solutions which corresponds to the SBCE activity 3.5: 'Communicate set to others' in Figure 6. The communication takes place in the form of a template, known as a 'System Concept Template', which is proposed to be the standard method to pass the information to the sub-system teams. The interviewed experts at Rolls-Royce suggested that the System Concept Template could also be used as a tool to communicate and review the generated design sets with customers to check whether the key value attributes identified at the SDR0 are actually met. The reason for this suggestion was that customers are sometimes uncertain about their needs and requirements at the beginning of the project. Therefore, as sets of solutions start to narrow down and more details are generated, the customers are more capable of clarifying their ideas and ensuring that the value definition is thoroughly communicated (Al-Ashaab et al, 2013). However, the logic of design tools and methods selection mapped behind the SDR0 and SDR1 activities was mostly based on expert's judgement within the collaborative company and the best practice of the research. It resulted in the need of creating practical guidelines for system designers to follow in order to enable the optimum selection of the design tools and methods in the SBD environment.

3.2 RR-LeanPD process model further enhancement

The RR-LeanPD process models shown in Figure 18 and 19 underwent further enhancement as part of the continuous improvement activities. The main goals of this stage enhancement were: the simplification of the language used and the reduction of the number of activities in order to make the processes 'leaner'. It was also very important to align the enhanced process model to the internal design practices within the collaborating company.

The next step in enhancing the RR-LeanPD process model was a slight alteration of the activities of the SDR0 and the SDR1 models, shown in Figures 18 and 19.

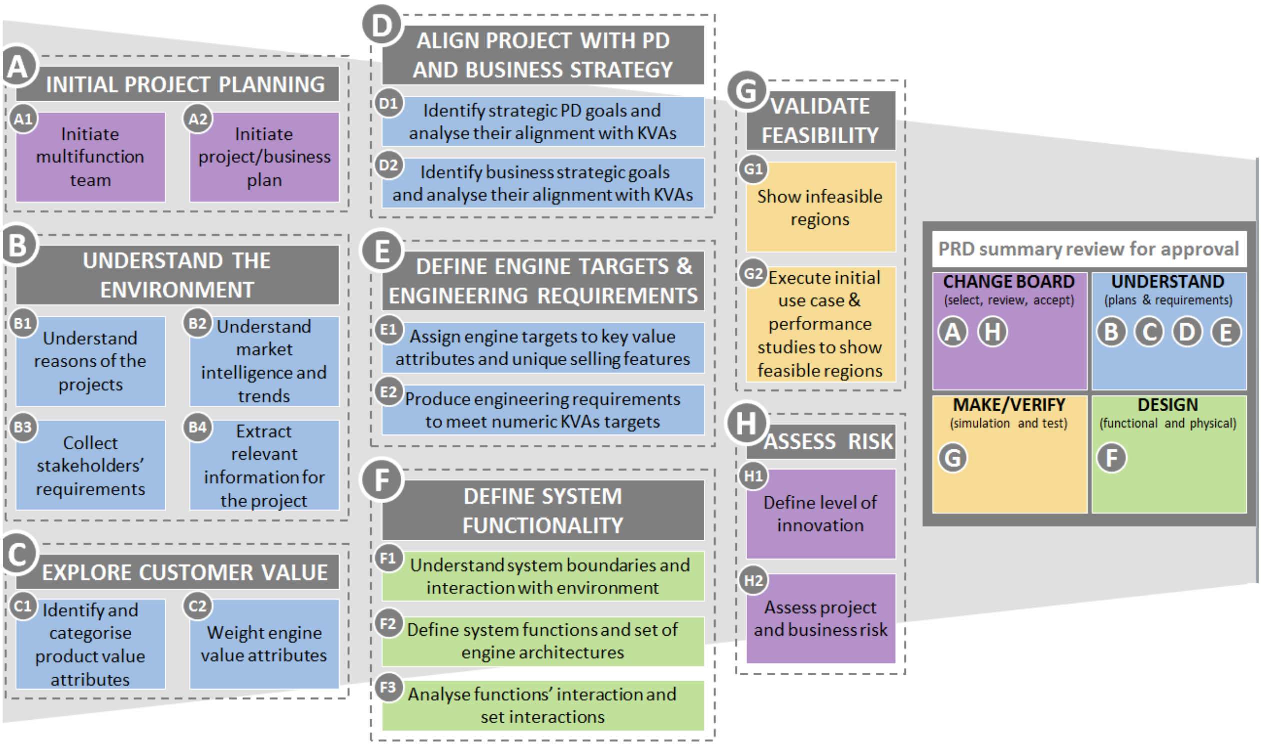

Figure 20: Modified SDR0 Lean PD templates for CONGA project (Rolls-Royce internal documentation, 2014)

Previous process models shown in Figures 18 and 19 were compared against internal Rolls-Royce general practice procedures, which resulted in a few alterations of the activities within the models in order to reflect the desired process model vision of the company:

The new SDR0 level process model shown in Figure 20 began with (A) 'Initial Project Planning' activity that contained two sub-activities 'Initiate multifunction team' and 'Initiate project/business plan' that replaced (A) 'Market study benchmarking' shown in Figure 18. This change specified the actions required for the activity by adding the sub-activities and by using the language familiar to system designers within the collaborative company. The next activity (B) 'Understand the environment' replaced (B) 'Collect data' activity in Figure 18. The four sub-activities within followed the same process logic except defining the level of innovation which was transferred to the activity (H) - 'Assess Risk'. The following activity (C) ' Explore customer value' contained two sub-sets instead of four, shown in Figure 18; the aim of the sub-activities was exactly the same they just combined four steps into two, listing the actions required and broadening the scope of each of the sub-activities. The activity (D) 'Align project with PD and business strategy' underwent similar changes to step (C), - four sub-activities were reduced to two by listing the same process actions required as per process model shown in Figure 18.

The next activity (E) ’Define engine targets & engineering requirements’ was new to the SDR0 process model. It enabled to assign engine targets to key value attributes and unique selling features as well as to produce engineering requirements to meet the numeric key value attribute targets. This activity aimed to define product target before defining the functionality of the product and by producing the engineering requirements to meet the target which was supposed to ease the definition of the functionality of the product. Activity (F) ‘Define system functionality’ borrowed exactly the same sub-activities and the process logic with an exception of a slight rewording not altering the aim of the sub-activities, shown in Figure 18.

The following two activities (G) ‘Validate feasibility’ and (H) ‘Access risk’ were new to the SDR0 process model. They enabled the analysis of the infeasible product regions that now led to an exploration of the technology readiness levels. Activity ‘Validate feasibility’ also involved some performance studies in order to show the feasible regions of the project; the aim of this sub-activity was to generate some preliminary performance calculations in order to understand the boundaries of the feasible regions and to define the expected performance levels of the new product e.g. maximum thrust, fuel consumption, configuration of the shafts, approximate weight etc. The next activity ‘Access risk’ contained two sub-activities ‘Define level of innovation’ that was transferred from ‘Collect data’ step shown in Figure 18, and ‘Assess project and business risk’. The whole SDR0 cycle ended after producing a PRD (Product Requirements Document) summary that incorporated four main phases of the design cycle within the collaborative company – understand, design, make/verify, change – captured in a four-box chart type of format to be presented at the SDR0 meeting. The four phases of the design cycle were colour coded in order to reflect that the output of the different activities within each design cycle will be reported within the associated section of the PRD document.

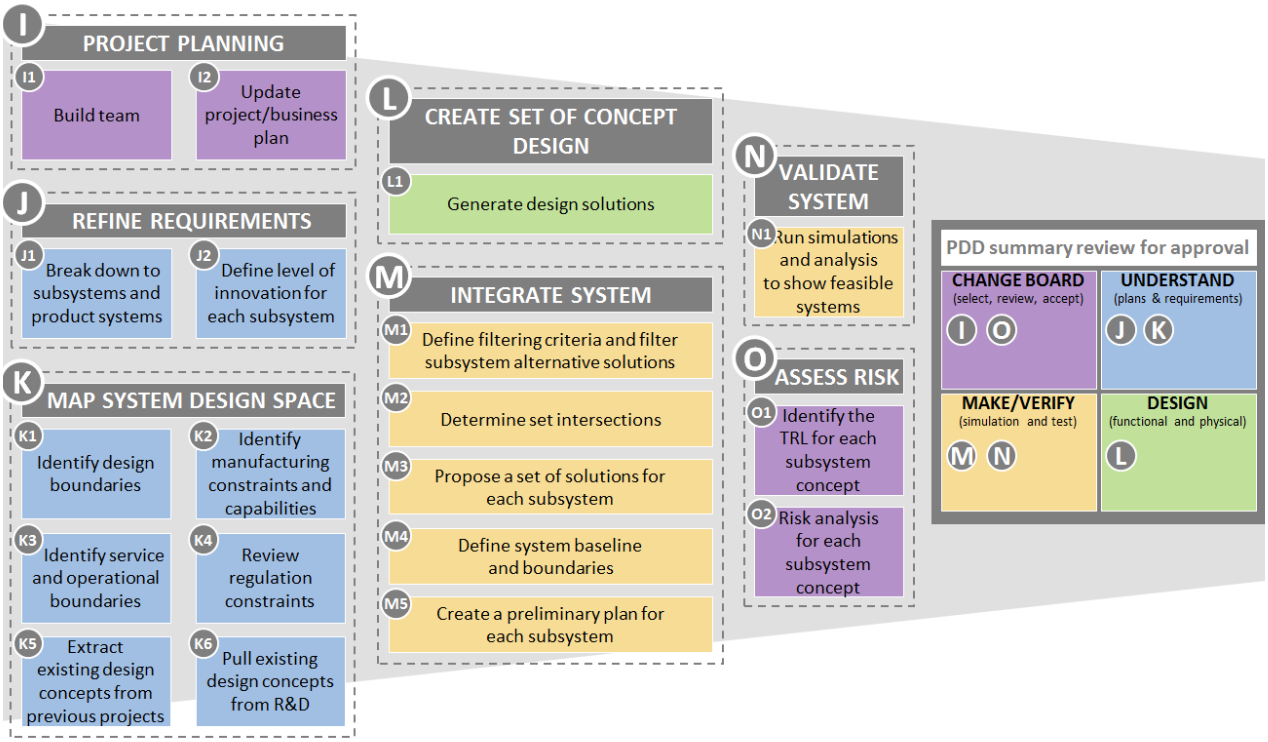

Figure 21: Modified SDR1 Lean PD templates for CONGA project (Rolls-Royce internal documentation, 2014)

The SDR1 process model also had to be altered in order to simplify the language and shape the RR-LeanPD process model principles to Rolls-Royce's vision of improving the SBD process model further: The SDR1 cycle began with an activity (I) 'Project planning' which contained two sub-activities 'Build team', and 'Update project/business plan'. The aim of adding this activity was to make sure that the requirements and their changes are captured and recorded at each phase of the preliminary design process. The following activity (J) 'Refine requirements' aimed to break down to subsystems and product systems defining the level of innovation of each subsystem. These two sub-activities were taken from (F) 'Define architecture and establish targets' sub-activity, shown in Figure 19. The aim of the process was exactly the same apart from the sub-activities sequence alteration that reflected collaborating company's vision of the improved SBD process model more precisely. The next activity (K) 'Map system design space' referred to system level activity rather than 'Map design space' shown in Figure 19. It specified the types of constrains to be identified by adding service and operational constraints analysis as well as review of regulation constraints however the aim of the activity was exactly the same – to understand the boundaries of the system and the feasible regions by analysing various constraints. The enhanced SDR1 process model contained a new activity (L) 'Create set of concept design' that aimed to generate design solutions. The following activity (M) 'Integrate system' contained exactly the same activities as (H) 'Filter alternatives' shown in Figure 19 except from TRL identification which was moved to (O) 'Assess risk' activity. The enhanced model also contained (N) 'Validate system' activity that aimed to run simulation and analysis tools to show the feasible systems.

The whole cycle ended after producing a PDD (Product Definition Document) summary that followed the same structure and logic as PRD summary four-box chart (shown in Figure 21) to be presented at the SDR0 meeting.

The reconstruction of SDR0 and SRD1 process models enabled the customisation of the preliminary design process view within Rolls-Royce by further incorporating SBD conceptuality and altering the sequence of the activities and sub-activities within. It adopted the same principles used in developing the RR-LeanPD model (shown in Figures 18 and 19); however the activities were rearranged in order to align to Rolls-Royce's internal design practices.

The design tools and methods selection logic mapped behind each of the activities that enabled to generate required outputs of RR-LeanPD process model was addressed during the reconstruction of both process models - SDR0 and SDR1. The selection was based on expert's judgement, the best practice within the collaborative company and subjective opinion of the research team. This resulted in questioning how accurate the selection of design tools and methods and the optimisation of the whole application were. Hence, these issues became the main driver of the MSc by Research reported in this thesis which is addressed in detail in the next chapter.

3.3 A development of a Rolls-Royce Set-Based design (RR-SBD) process model

The development of the RR-LeanPD process model presented in the previous section called the attention of many system designers within Rolls-Royce. However, they requested to focus mainly on the preliminary design phase of the system level. In addition, it was decided to address the enhanced process model from a possible collaborative perspective between the power-plant and the airframer due to a new project launched funded by the Innovate UK called CONGA (Concept Optimization Of Next Generation Airfraft). The project involved three key players – the aircraft (simulated) the powerplant (Rolls-Royce) and the airframer (Airbus).

The CONGA project was used to take the enhanced RR-LeanPD process model one stage further by: a.) including the collaborative perspective goals b.) modifying SDR0/SDR1 process models in order to customize their outputs to meet Rolls-Royce needs c.) altering the selection of the design tools and methods to enable effective application of the different process model activities.

The aim of altering SDR0 and SDR1 process model in order to customise their outputs to meet Rolls-Royce needs was to transfer a few activities from SDR1 to SDR0. It was very important to assure that SDR0 gates were not passed until the requirements were fully understood. In order to do so it was acknowledged that an exploration of the design space might be required in certain project scenarios at the very early stage of the preliminary design. The other activity involved research work of design tools and methods enabling SBD and agreed logic (between various experts at Rolls-Royce and the research team) of matching these tools behind the activities of SDR0 and SDR1. This new model is called Rolls-Royce Set-Based Design Collaborative Process Model (RR-SBD). Figure 22 presents a graphical model of the new process model developed under the collaborative process principles for Rolls-Royce. The different roles of the participants were assigned to colour coded swim lanes graphical representation that showed how process documents could be flown from one complex analysis system to internal and external collaboration zones between the key players of the collaborative process and the various departments within each of the collaborating company. The further enhancement of the RR-SBD collaborative process model was supposed to be represented and operated within this framework.

The CONGA project enabled the enhancement of the Rolls-Royce Lean PD model one stage further by developing a process model which incorporated the logic of the altered templates and the collaborative perspective combined with the possibilities to capture and share the generated design data during the process by developing a RR-SBD collaborative process model, see Figure 22.

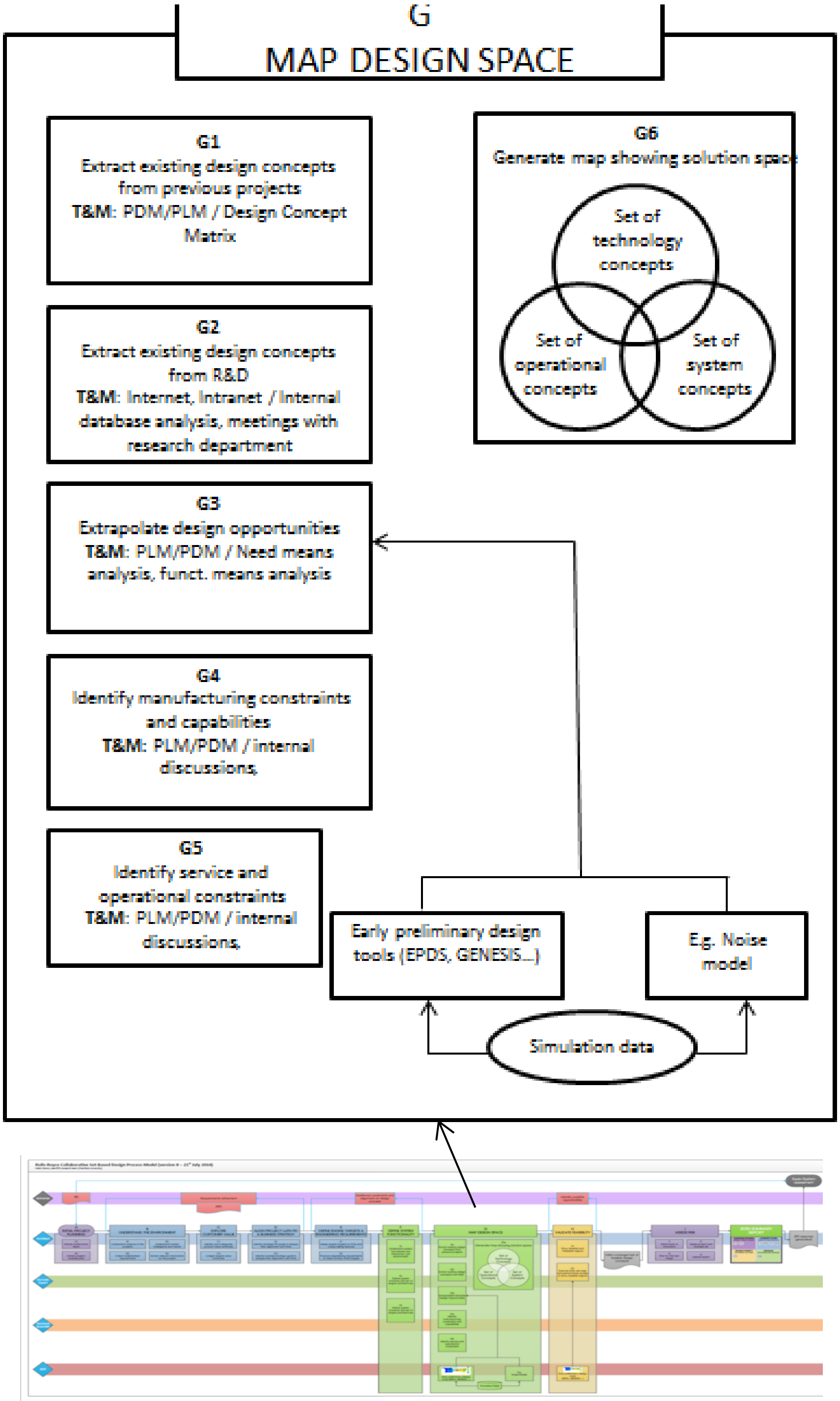

Figure 222: Rolls-Royce – SBD collaborative process model (CONGA, 2014)

The key set of activities that demonstrate the core principle of the SBD – the development of a set of design solutions is 'Map Design Phase', shown in Figure 22. It enables the generation of the design solutions in parallel which assures that the main principle of SBD is being adopted by the company.

The activity 'Map design space' aims to define feasible regions of the design space and to identify and explore sets of (multiple) concepts. This design step is divided into six sub-steps to secure the completeness of the activity; each of the sub-steps recommends design tools and methods that support SBD principles:

G1 "Extract existing design concepts from previous projects" aims to identify already existing products that help to define the design space sets.

G2 "Extract existing design concepts from R&D" aims to identify already existing technologies which have the potential to provide detail and expand the design space sets.

G3 "Extrapolate/calculate design opportunities" guide engineer(s) to perform system modelling and simulation studies to further expand and provide detail to the design space sets.

G4 "Identify manufacturing constraints and capabilities" aims to explore how manufacturing capability can expand or constrain the design space sets.

G5 "Identify service and operational constraints" aims to explore how the in-service operations capability can expand or constrain the design space sets.

G6 "Generate map showing solution space" aims to show the full solution space and how design space sets intersect. The intersection can then be used in the next step to narrow down to a feasible region.

This collaborative perspective process model step aims to be iterative by nature meaning that the results gained from the design activities are sent back to the airframer who then may request new iterations due to the new requirements by the stakeholders added or certain changes to the existing set of requirements.

Figure 22 presents a great achievement in supporting the true principles of the SBD application within Rolls-Royce PD. However, it was obvious that a lack of a simplified guide to introduce the enhanced process model to system designers was present. Therefore, it was decided to convert the RR-SBD collaborative process model into a platform independent SBD Navigator, linked to company's databases that would enable guiding the system designers through the application of different SBD activities in a leaner manner. The tool was supposed to incorporate collaborative perspective with the airframer, mapped out in CONGA's project. However, it was planned to include only powerplant's detailed PD preliminary design processes represented by the RR-SBD collaborative process model shown in Figure 22. This was due to the intellectual property laws and regulations (based on the initiative to develop the new tool platform only by Rolls-Royce).

The latest version of the RR-SBD collaborative process model shown in Figure 22 was improved significantly and it was also brought closer to the real design practices of the company. More work was carried out in selecting the best design tools and methods that could enable different SBD activities as well, which will be presented in chapters 4 and 5.

4. DESIGN TOOLS AND METHODS SELECTION WITHIN RR-SBD PROCESS MODEL

4.1 Global Toolset matrix main principles

Rolls-Royce's internal processes have been examined in order to understand their decision making points and to analyse new design methods and tools documentation processes. In order to complete system design tasks, occasionally bespoke tools are required to be developed. The description and the best practice of using these new tools are recorded on the company's intranet webpage called 'Global Toolset'. The Global Toolset contains a set of web pages created to keep the records of the bespoke and standard design tools being used within different departments / sites of the company around the world. A special procedure has been set up to approve and globalize these tools.

The Global Toolset matrix purpose is to have all of the design tools and methods listed and organised in one place in order to enable the capture and sharing of them among different sites. However, the matrix does not automatically generate or suggest how and when the tool or method should be used in SBD environment within Rolls-Royce. This problem highlighted a need to develop a tool capable of selecting different design tools and methods to enable an effective RR-SBD collaborative process model application, which is presented in the next section.

Figure 23 shows a snapshot of the top level of the Global Toolset matrix interface. The horizontal column of the table represents key attributes of the product while the vertical represents key subsystems or product systems. There are less than 100 standard and bespoke tools listed currently at the different levels of the matrix.

Bold - Applicable to Stg 0 & 1
Normal - Applicable to Stg 1
Italic - Applicable to Stg 0

SubSystem or Product System		Attributes					
		Functional design	Physical design	Mechanical integrity	Emissions	Noise	Low Observables (Radar, IR)
SubSystem	Installations & Controls						
	Fans						
	Compressors						
	Combustion and Casing						
	Turbines						
	Rotatives			**Shaft Sizing Tool - 2 shafts** **Shaft Sizing Tool - 3 shafts**			
	Transmission Structures and Drive		**Bearing Tool** **Ball Bearing Tool** **Double Helical Gap Tool**				
	Integration with Airframer related Systems						

Figure 233: Rolls-Royce Global Toolset Matrix documenting available design tools (Rolls-Royce, 2015)

As shown in Figure 24 each tool or method placed within the matrix needs to be documented in a specific way: each page has to state who is the point of contact in case of more information of the tool is required; who is the tool franchised by; the brief description of the tool and the four links of: the export control statement, download methods (tools may contain various supporting data formats), how to guide, and the link to the tool being discussed.

The Global Toolset Matrix benefits users by incorporating and displaying all design tools and methods approved by the company, however the interface is static and it does not generate design tools itself. Even though the users can submit new tools or request for more information this process is spread across various people whose engagement in the process varies depending on the role and skills required. This very often results in delays advising users or implementing new functionality of the matrix.

The matrix was not linked to SBD collaborative process model which resulted in the need of creating a Microsoft Office Excel based spreadsheet displaying preliminary design different stages (SDR0 and SDR1), colour-coded phases (understand, design, make/verify and change) and design tools and methods enabling the design activities defined in RR-SBD collaborative process model, see Figure 25.

TOOL: Ball Bearing Tool

Point of Contact:
Franchised by:TBD

Description:
The workbook allows quick selection and preliminary analysis of ball bearings. By inputting the load and speed conditions and selecting a bearing size the stress, life, lube required, and data such as dN are calculated. The BB Finder (Ball Bearing Finder) sheet will check all of the sizes in the database and various pitch diameters in each size to determine which bearing sizes meet the input criteria. It will list the best bearing size to meet each of the given criteria from the list of acceptable selections.

Downloads Export Control
Export Control Document - click to download

Download methods
Methods are included in the 'How-To-Guide' and references.

How-to-Guide
How to Guide for the tool is an included sheet in the tool.

Download Tool
Ball Bearing Tool - click to download

Figure 244: Bespoke tool example (Global Toolset Matrix, Rolls-Royce, 2015)

The more complex products are being developed by the company the more complicated procedures tend to be designed in order to assure the completeness of the final product and the satisfaction of the stakeholders and the customer. In some cases permission to view certain design data spread across various company's resources can take time. And even after getting the access to the required resources it can be difficult to understand the aim of the tool due to the tacit knowledge used by the author of the tool application. To address these possible obstacles it was agreed that a computerised tool selector – a SBD Navigator, presented in chapter 5, could be a great solution in guiding system designers via the preliminary design by introducing SBD principles from a collaborative perspective and also by promoting new general design tools and methods when these become available. The aim of this software was to shortly introduce the purpose of the tool and to give a short description how to adopt it for particular design tasks by adding links to the best practice and lessons learnt while following the enhanced process model steps. The Microsoft Office Excel spreadsheet shown in figure 25 was used as a source document for the software coding work. The SBD Navigator initially incorporated main structure of the RR-SBD collaborative process model which was later modified after new requirements and the initial feedback from the potential users had been received.

4.2 Mapping design tools and methods into the SBD linear steps spreadsheet

As mentioned in the previous section the Global Toolset Matrix captured and documented different design tools and methods and their best practice based on the subjective opinion of the different designers and engineers. It was not linked directly to the RR-SBD process model, shown in Figure 22. The work presented in this section is about associating different design tools and methods with the activities of the SBD process model. These activities have been arranged in a linear manner using a typical Microsoft Office Excel spreadsheet, shown in Figure 25. This spreadsheet is an updated version (a sub-section) of the spreadsheet, shown in Figure 16 (of recommended tools and methods to be used to support different activities of SBCE/SBD). The author of this research studied each of the SBD activities and then selected different design tools and methods to enable them. The spreadsheet was then revised by different experts within the collaborating company. It was agreed that the selection of the design tools and methods would be grounded on the best practice of the company captured in the Global

Toolset Matrix, shown in Figure 23, as well as the latest research findings (see section 2.5).

The creation of the linear steps spreadsheet provided these following benefits:

1. It gave a mechanism to visualise the SBD process model activities and the different tools and methods enabling these activities.
2. The spreadsheet was seen as a first step towards the development of the tool selector – SBD Navigator.
3. It captured the best practice of the SBD process model activities in a logical manner.
4. It eliminated the possibility of the duplication of the design tools and methods in different preliminary design activities.

It also highlighted the following issues:

1. Having a static manner of documenting the design tools and methods (Global Toolset Matrix) was not an optimal way of supporting system design activities.
2. There was a need to have a more dynamic and interactive manner of selecting the tool for the SBD activities.

PD Tools	Tool description	SBD PROCESS MODEL STEPS TO BE COMPLETED BEFORE SDR0 (SYSTEM DESIGN REVIEW)																		
		Initiate Multi-functional Team	Initiate project plan	Understand resons for the project	Understand market intelligence and trends	Extract information relevant to project	Collect stakeholders' requirements	Identify and categorise product value attributes	Weight engine value attributes	Identify strategic PD goals & analyse their alignemnt with key value attributes	Identify business strategic golas and analyse their alignment with key value	Assign system targets: key value attributes & unique selling features	Produce engineering requirements to meet numeric key value attribute targets	Understand system boundaries and interaction with environment	Analyse functions' interactions & set interactions	Define system functions and sets	Show infeasible regions	Execute initial use case and performance studies to show feasible regions	Define level of innovation	Assess project and business risk
		SELECTION OF PD TOOLS FOR CERTAIN DESIGN ACTIVITIES WITHIN SDR0																		
Organisational Tree	Branching Diagram Showing Hierarchical Structure of Organisation	X																		
WID	Work Instruction Document		X																	
SEMP	Service Engineering Management Plan		X																	
IP	Improvement Plan		X																	
Root Cause Analysis	A class of problem solving methods aimed at identifying the root causes of problems or incidents			X																
Sensitivity Analysis																				
Functional Flow Diagram	Shows Interactions Between Functions														X					
AHP	Used to Rank Key Value Attributes								X											
Qualica	Software to assist in the production of AHP Matrices								X											
Stakeholder Analysis	Determine Relation Between Requirements and Stakeholders					X														
Stakeholder Influence Map	Shows Interaction Between Stakeholders					X														
Systemic Textual Analysis	A technique enabling the creation and documentation of a clear set of unambiguous technical requirements, generally from text-based sources					X														
System Boundary Diagram	Marks out Boundary of System													X						
Context Diagram	Contextualises System Operation													X						
Affinity Diagram	A tool to organize and consolidate information concerning a product, process, complex issue, or problem																			
Market Benchmarking	Sets Baseline for New Product Market				X															
Competitive Intelligence	Analyse Competitor Products and Patents				X															

Figure 255: A sub-section of the linear SBD process model spreadsheet, showing the colour code division principles, 2014

This spreadsheet became a foundation for a development of the initial design tools and methods selector for the RR-SBD collaborative process model, which is presented in the next section.

5. THE DEVELOPMENT OF THE SBD NAVIGATOR

5.1 The evolving issue of the RR-SBD process model

The integration of the SBD principles into the Rolls-Royce SDI process model produced a promising improvement in the PD process of the company. The ability to develop a set of design solutions in parallel by analysing high risk solutions aside to 'safer' options increased company's innovation possibilities. A need to capture and share the knowledge gained during the preliminary design phase increased the learning intensity in each design cycle. The principle of the SBD to test the solution before actually designing it (by prototyping, simulating, testing) enhanced the knowledge based environment concept. The gradual narrowing of the solutions also meant that the number of the design changes and rework will be significantly reduced due to the higher level of analysis carried out before selecting the optimum design solution. This in return resulted in reduced product time to the market and reduced project cost. The novel process model was meant to increase the quality of the product too, by enabling to develop an optimum solution, well tested before the design phase.

The final RR-SBD collaborative perspective process model presented in Figure 22, called the attention of various system designers across different departments within Rolls-Royce. However, it also highlighted some important issues needed to be considered as part of the continuous improvement of the PD process:

- A need to have a simpler mechanism to guide the end user applying the activities of the RR-SBD collaborative process model.
- A need to match/align the terminology used at Rolls-Royce to the enhanced RR-SBD collaborative process model.
- A need to have a software version of the process model that could be integrated within the current Siemens PLM system.
- A need to enhance the allocation/selection of the different design tools and methods in order to enable the RR-SBD collaborative process model.

- A need to develop possible mobile platform software to guide and navigate the end user within the RR-SBD collaborative process model.

- A need to develop a mechanism to share the opinion and the rationale of the decisions taken within the RR-SBD collaborative process model.

The following are the steps that the author took to capture and analyse the evolving issue of improving the RR-SBD collaborative process model:

- Attendance of regular meetings such as design review meetings, Global Toolset Matrix related meetings.

- Dedicated CONGA project workshops between the LeanPPD research team of Cranfield University and Rolls-Royce.

- Meetings with subject matter experts of the collaborating company to understand preliminary design activities.

- Meetings with the system design expert to clarify internal procedures and their purposes.

5.2 Robust Design Cycles integration into the RR-SBD process model

The following section presents the integration of the robust design cycles into the RR-SBD collaborative process model.

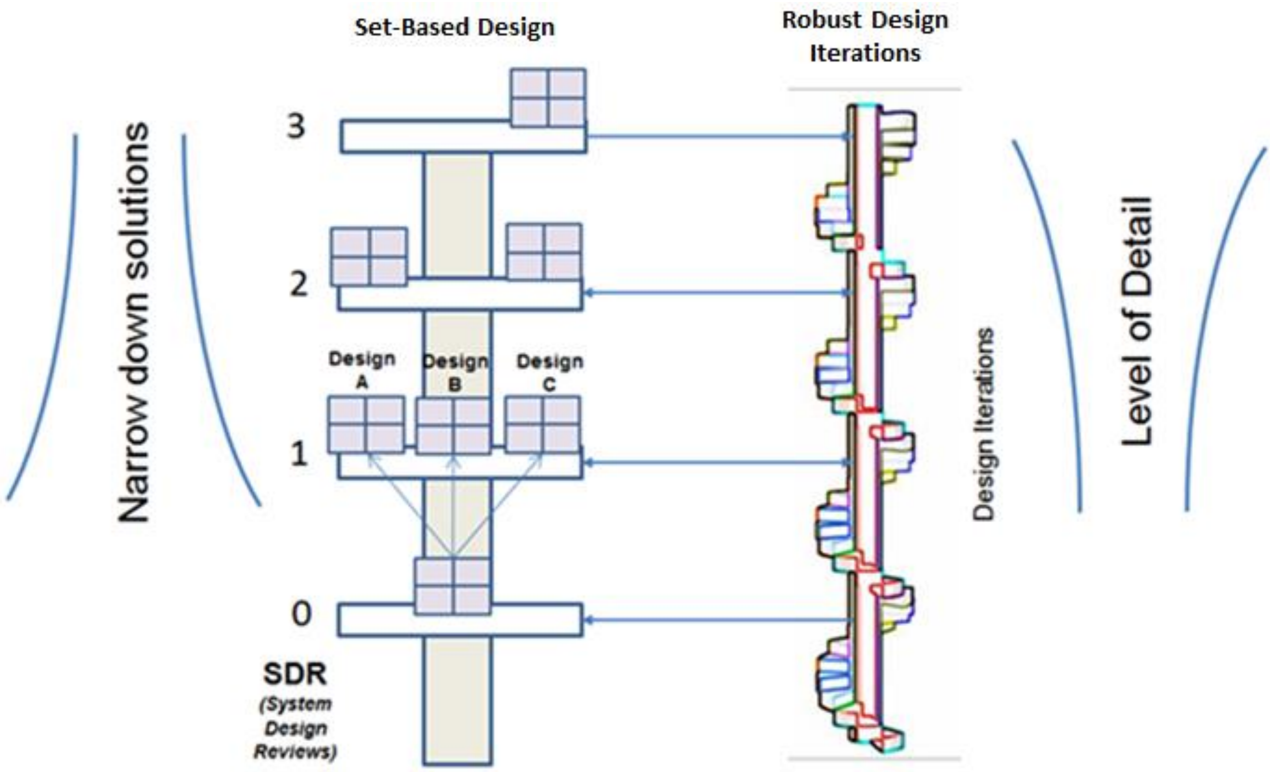

Figure 266: RR-SBD process model integration with Robust Design Cycles (Parsons, 2014)

In SBD environment the design sets developed in parallel are tested and analysed as the design progresses. The process of narrowing down the design options aims to select the optimised design solution that best satisfies the requirements of the stakeholders involved, as discussed in chapter 3. In order to create robust design sets Rolls-Royce has developed a conceptual model shown in Figure 26, that grounds robustness conceptuality on staircase different colour steps example. 'Robustness' is defined as the insensitivity to sources of unwanted variation or noise factors (Hasenkamp et al, 2008). Taguchi defines noise factors as potential sources of variation that cannot be controlled by the designer. Noise factor is a term popularized by Taguchi within Parameter Design, of which the objective is to select the optimum levels for the controllable system parameters, so that a product is functional (Dean, 1991).

Looking from the bottom level up of the model the design sets get rejected accordingly to their ability to satisfy the stakeholders' requirements. The staircase colour coded model matches the internal processes, tools and methods to be adopted in order to develop robust design solutions at Rolls-Royce. These steps specify the design method, the software and the database to be used at each step of the design process in order to reach the review of the tollgates by presenting the SBD principles. As the solutions get narrowed their level of detail (analysis, testing or prototyping) increases. The Robust Design Cycle concept aligns with company's design tollgate timescales. The reason for adding this new concept into RR-SBD collaborative process model is the possibility to integrate new SBD conceptuality aside to the best practice of Rolls-Royce. The RDC1 aligns to SDR0 (System Design Review – the first level of Rolls-Royce's design tollgate) and is ended after presenting the Product Requirement Document at the design review meeting.

5.3 The development of a SBD Navigator

The evolving PD issues discussed in the previous section led Rolls-Royce to propose a development of a platform independent SBD Navigator for the RR-SBD collaborative process model, presented in Figure 27. The computerised software tool is called – 'Set-Based design Navigator', which could work either as independent platform or in conjunction with Siemens TeamCentre Mobility App or the Siemens JT2Go software. A spreadsheet with initial functional, availability, user experience and other requirements was created shortly. It covered IT platform, layout and main functionality topics of the required tool.

The aim of the functional requirements was to assure that the tool will provide guidance through various scales of the design process by informing the end users of the best approaches to carry out system design tasks. Many functional requirements could not be presented in this research due to the confidentiality issues. However, six requirements have been listed as examples to show the key functionality of the tool:

1. The tool shall guide the user through various scales of the design process, providing the information at each stage. (It was very important to reflect a scalable view of the process showing past and future design activities of a particular design step.)

2. The tool shall clearly show the position of the designer in the design process. (Due to the complexity of the processes involved in the preliminary design phase it was very important for the tool to quickly assess the position of the system designer within the process.)
3. The tool shall display several scales of the process.
4. The tool shall explain the purpose of each step in the design process. (The tool was supposed to be self-explanatory due to a large amount of preliminary design data to be introduced.)
5. The tool shall display generic inputs and outputs of each step in the design process. (It had to clearly explain and distinguish the inputs and outputs for each activity. The tool had to explain the purpose of each design activity in order to clarify the suggested route for the system designer to follow while transforming the design inputs into outputs.)
6. The tool shall show how each input is transformed into each output via activities.

This set of requirements was constantly supplemented with additional specifications after reviewing the aim and objectives of the required functionality of the tool.

The core development of the SBD Navigator software was subcontracted to a professional software development company. The subcontractor engaged in creating a stand-alone, distributable ‘demo’ version of the SBD Navigator, initially based on iOS platform. In order to make it available to potential users the developer had to install the SBD Navigator on iPads using Apple standard distribution mechanisms. The initial demo version was supposed to be tested by the potential users and with the help of the author of this research the new requirements gathered had to be incorporated into the second iteration of the software. It was agreed that the development process would be iterative by nature meaning that every time new feedback or requirements were received they had to be incorporated into the software code reflecting the change.

It was decided to follow the agile development manner of the SBD Navigator meaning that motivated and empowered software developers – relying on technical excellence and simple designs – create business value by delivering working software to users at regular short intervals. At the core of these practices is the idea of self-organizing teams whose members are not only collocated but also work at a pace that sustains their creativity and productivity. The principles encourage practices that accommodate change in requirements at any stage of the development process. Furthermore, customers are actively involved in the development process, facilitating feedback and reflection that can lead to more satisfying outcomes (Dingsoyr et al., 2012).

5.4 Architecture and main functionality of the SBD Navigator

This section presents the software architecture and the main functionality of the SBD Navigator developed to guide system designers through the SBD preliminary phase at Rolls-Royce. The concept of the navigator is intended to support the following three project scenarios: 1) development of a new engine (system level) concept 2) development of a modification of an existing engine system/subsystem architecture 3) development of a modification of an existing subsystem or component due to in service failure. This research is concerned with only new engine (system level) development. The architecture design is part of the development of the SBD Navigator and it is presented in the following section.

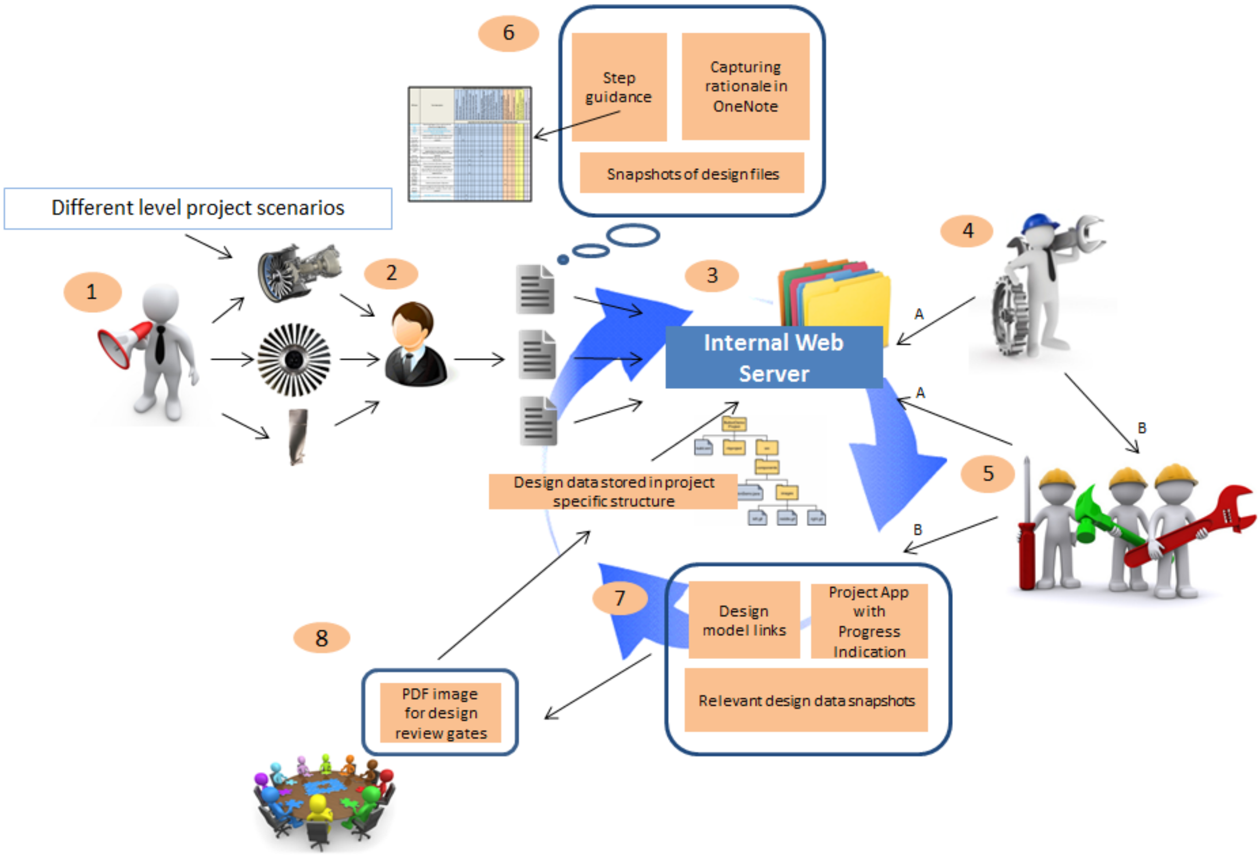

Figure 277: IT architecture of the tool selector

Figure 27 illustrates the software architecture of the SBD Navigator. The logic of this architecture was defined by reviewing existing process principles at Rolls-Royce and then incorporating the desired functionality of the SBD. The main key players were selected based on the existing process model of the collaborative company adding a tool administrator (the researcher) who was responsible for adjusting the templates of the SBD navigator and making the changes to the Linear steps spreadsheet, (see figure 25) after they had been approved and communicated by the research team and the expert within Rolls-Royce. The architecture also reflects the iterative communication nature between the tool administrator, the stakeholders of the process and the software development company. Every time the templates were re-coded by the tool administrator, they were sent to the software development company for further incorporation into their source code. A simplified version of the RR-SBD collaborative process model was converted into three SBD Navigator templates representing three different project scenarios based on the linear steps spreadsheet, explained and presented in Figure 25. The author of this research with the help of the system design expert aligned the RR-SBD collaborative process model, shown in Figure 22, to Rolls-Royce's internal general quality procedures. The general quality procedures form a design quality system within the company which assures the satisfaction of the stakeholders involved in the design process by meeting their requirements. This alignment enabled a generation of three different templates of the RR-SBD collaborative process model. The logic of the process division of these templates was mainly based on general quality procedures for full scale and modification project. Each scenario followed a different sequence of the SBD collaborative process model activities as determined in general quality procedures. The start of the SBD Navigator guiding process is initiated by the chief designer (represented in Figure 27, No. 1) of the engine system under the development who instructs the tool administrator (which is the author of this research, No. 2) to create the templates that represent the SBD activities needed to be followed in order to perform one of the listed project scenarios. The administrator makes JSON (an open standard format that uses human-readable text to transfer data objects consisting of attribute-value pairs, it is most often used for the transfer of the data between a server and the web application, as an alternative to XML (JSON, 2015)) file modification based on the general quality procedures aligned to the SBD process principles mapped on the linear SBD process steps spreadsheet. The code is then sent back in an appropriate format to the software developer who applies the changes to their system and produces the templates requested. These templates are then placed within the Internal Web Server (IWS). The technical lead accesses the right template within the IWS, informs system designers of the ready to use template stored within the IWS, (No. 4, activities A, B). The system designer(s) (represented in number 5, activities A, B) accesses the selected process model that represents the right project scenario via the navigator interface and begins the design work required. Each template consists of main standard attributes (No. 6): step guidance (design tools and methods suggested for each design activity that encourages SBD, OneNote pages allowing to capture the rationale behind the decision making and space for snapshots of output images from the parallel and historical projects that enable the search of relevant information. No 7 represents the functionality of the software after the system designer has made some progress: each template has task completion indicators that the system designer and/or the technical lead are responsible for. System designers are able to add relevant links to the design models supporting the design work as well as to take snapshots of the design data in various formats from different data sources. Another important feature at this stage is OneNote functionality that opens an active OneNote workbook for each project allowing the project to be seen in steps progress (evolutional) view and to display the rationale behind the decision making. Once the design cycle is completed, the software allows the creation of a four box chart in PDF format presenting the problem of the cycle and the steps that have led to the solution for the design review gate, activity 8. All the documentation created during this process is stored in a project specific structure on IWS for future design projects to access, - in order to promote knowledge based design environment (capture and sharing of design data).

The spreadsheet with SBD enabling tools and methods was further adjusted and complimented by introducing Rolls-Royce's internal preliminary design phases by applying a colour code which matched the internal company's design steps colour coding rules. An additional task of identifying possible software options for each of the listed design tools and methods, followed shortly. The logic behind these activities was mostly based on the best practice of the company, the recent research findings of the preliminary design phase from CONGA project and also some general research points.

The SBD tools and methods spreadsheet, populated with the internal Rolls-Royce's general quality practice procedures and links to the intranet resources, taking into account the best practice and lessons learnt (company's intellectual property (IP)), became a foundation of the software development work. A sub-section of the spreadsheet is reflected in the Figure 25, however due to IP regulations (the application contains company internal design and engineering procedures, best practice and lessons learnt) the full version of the application cannot be revealed.

5.5 SBD Navigator's graphical interface

Figure 288: User graphical interface for the SBD Navigator

This section presents the user graphical interface of the SBD Navigator. It explains the layout arrangement and the main functionality of the tool. Figure 28 represents the layout of the functional prototype version (system level template). The preliminary design phase has been divided into Robust Design Cycles (RDCs) (Figure 28-1.), that match the timescales of the SDR gates (Rolls-Royce's tollgates). Each of the RDCs contain four main phases (understand (blue), design (gold), make (yellow), verify (purple)) within, which represents the development of the conceptual design solution, as explained in section 5.2. The phases have been coloured to match Rolls-Royce's internal colour code system. The completion levels are indicated by adjusting the measurement bar by the sytem designer or the technical lead (28-3) by carrying out the tasks of the design steps. Once the tasks have been fully completed they get manually ticked off (28-4) by the system designer at the design solution level. The middle column (Figure 28-2.) displays design steps from the collaborative perspetive adopted from the CONGA project that were customised by the researcher and the expert to meet the requirements of the system design work at Rolls-Royce. These steps have originated from the process model reflected in Figure 20. The colour code has been altered as well as the sequesnce of some of the steps within the first tollgate – SDR0 (RDC1), in order to address the areas of concern as requested by Rolls-Royce. Reading the titles of the steps from the bottom up, of the SBD navigator page (28-5), it becomes clear that the steps match activities B, C, D, E from the process model shown in figure 20. Some steps have been combined and some of the titles of the steps have been changed but the aim of the process has been kept, which is - to enable the SBD and to enhance the Lean PD principles. The blue colour set of steps stands for 'Understand' phase of the robust design cycle. The next set of steps shown in Figure 28 have been coloured in amber colour rather than in green as shown in Figure 20 in order to match company's internal colour code system more precisely. The amber set of steps stand for 'Design' phase of the robust design cycle. The aim of the steps has not changed either. Each of the steps can be activated by clicking individually on each of them and reading the descriptions and guidelines coded in, as explained in further Figures of this section. If the middle column was scrolled up the other two phases - 'Make' and 'Verify' would come up showing individual steps adopted from the process model shown in Figure 20, following the same colour coding rules.

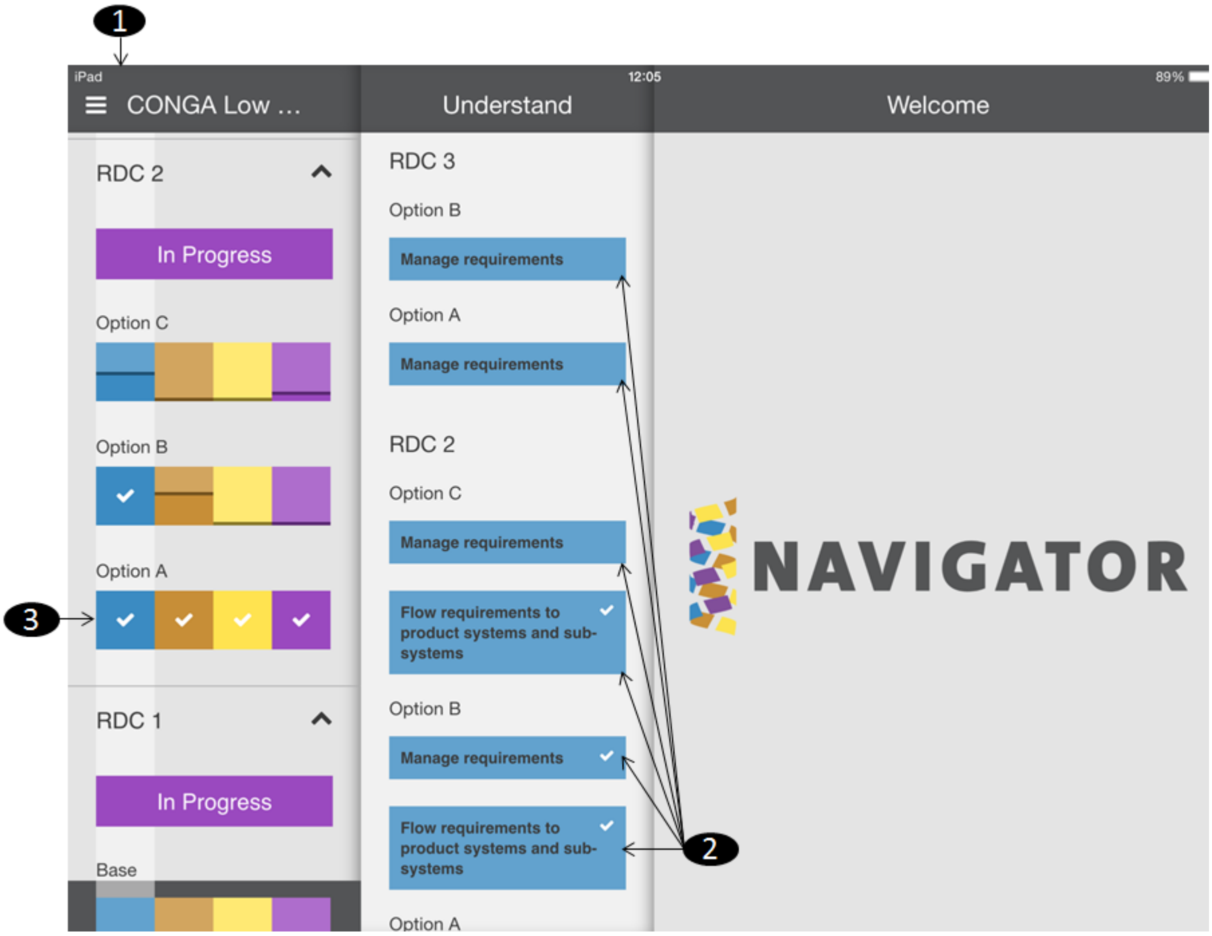

Figure 29: Slice view (design evolution) capability within the SBD Navigator

Figure 29 displays another graphical user interface which can be activated by pressing the the blue box shown at the very bottom of the column displaying the RDCs (Figure 28-6). This is the design evolution capability (Figure 29-1) within the SBD Navigator that enables to view the completeness levels of the activities as well as to analyse the steps taken in order to progress certain phase within the RDC by developing a set of design solutions in parallel. The evolutional view is useful when comparing a few sets of design solutions as it allows to understand the reasons behind the design rationale of different options and also to assess the maturity of the design sets. The evolutional view also reveals the design steps adopted from CONGA project only specific to the phase selected (Figure 29-2). This view provides with information which of the steps have been completed and which have not for each of the individual design solutions at certain phase level.

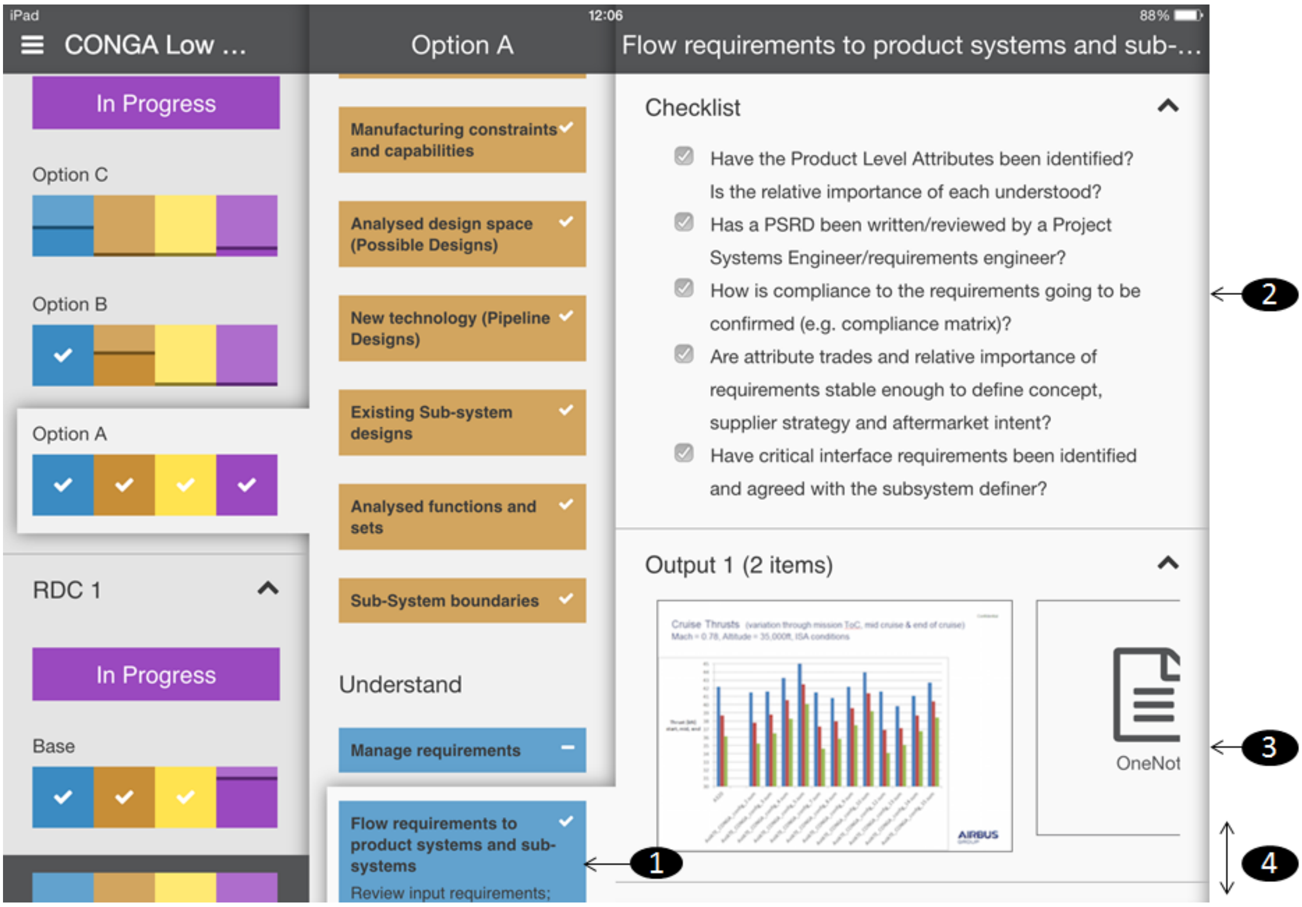

Figure 290: Structure of individual design steps within SBD Navigator

Figure 30 reflects the incorporation of the Rolls-Royce’s SDR checklists into the RR-SBD collaborative perspective process model (Figure 30-2.), adopted by the SBD Navigator. After selecting one of the design options (solutions) as shown in Figure 29-3. All of the design steps adopted from the RR-SBD collaborative perspective process model (see Figure 22) become visible in the middle column. By selecting one of the individual steps (Figure 30-1) the checklists of the design review specific to the selected step become visible as shown on the right of the SBD Navigator (Figure 30-3). The same page displays the ability to capture and store snapshots of the design data taken by the system designer or the technical lead (Figure 30-3). The snapshots can be taken from any data sources as long as they provide the needed information for the solution being designed together with a link taking to the original source of the design data. The checklists aim to be recommendatory nature displaying main steps and principles of the system design adopted by the company in order to successfully develop new products. The checklist shown in Figure 30-2 is a part of Rolls-Royce's quality system to be followed in order to satisfy the requirements of the stakeholders involved in the design process. These checklists apply mostly for full scale projects rather than for modification design work. The modification projects may not require all of the tasks from the checklist to be completed. However, it is much 'safer' to display the whole set of tasks required for a particular system design review as system designers may select applicable design checks themsleves recording the logic of this selection.

The aim of developing the SBD Navigator is not to overload it with large quantities of the design data but to enable visual guidance for the end user where such data can be found and advice the end users of the best ways how to achieve design goals for a particular design scenario.

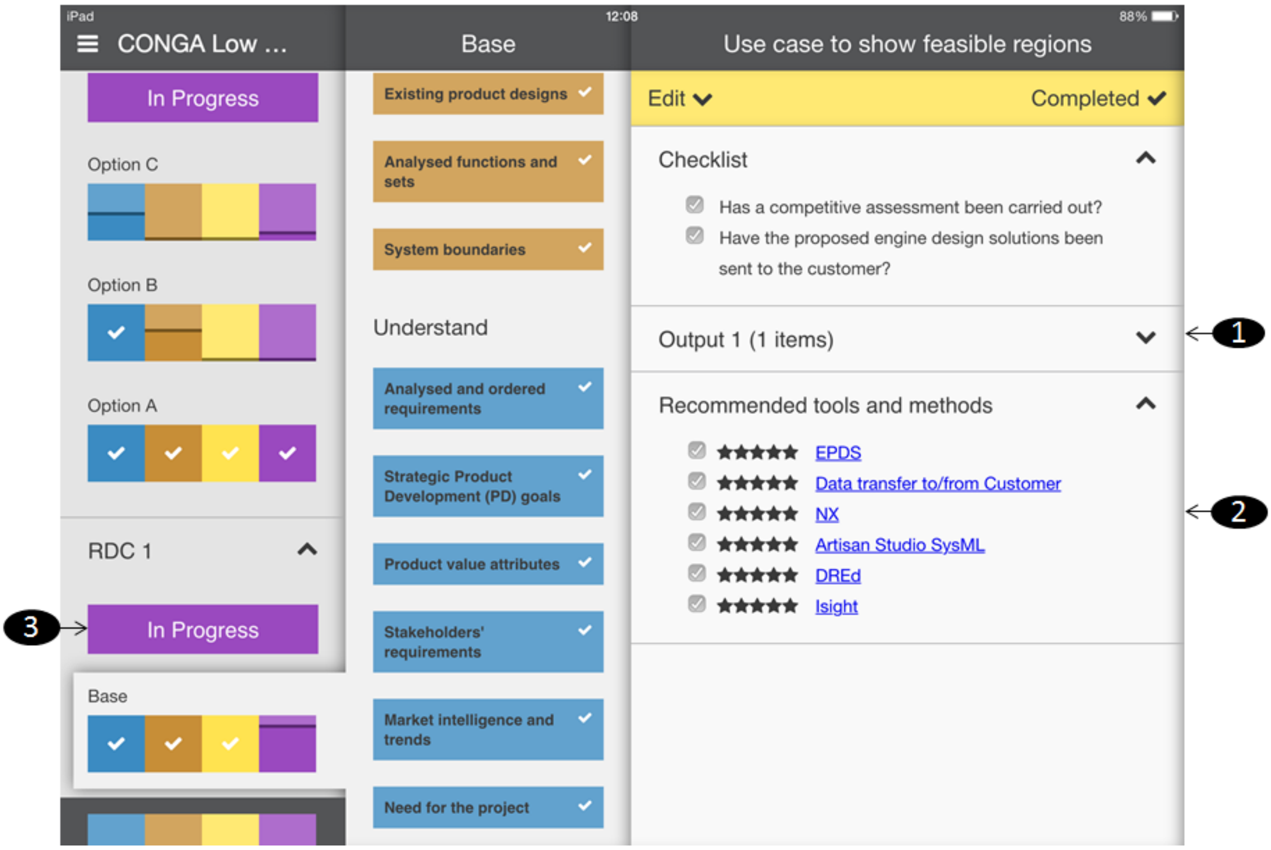

Figure 301: Example of recommended tools and methods for particular design step within SBD Navigator

Figure 31 presents the recommended design tools and methods. By scrolling down the right side of the SBD Navigator's graphical interface (Figure 30-4) the 'Recommended Tools and Methods' section opens as shown in Figure 31-2. The 'Output' section closes down leaving enough space for the recommended design tools and methods to be displayed (Figure 31-1). These design tools have been carefully selected in order to satisfy the goal of each activity within the RDC. The selection logic is mainly based on PD general research, best practice within Rolls-Royce (attending meetings, analysing lessons learnt and best practice sources within the company and getting advice from the system design experts). The logic of this selection has been reflected creating the linear steps spreadsheet explained in section 4.2, Figure 25.

The design methods that support the application of the design tools listed are being used by Rolls-Royce currently. A few suggestions to use a different variety of the design methods have been incorporated while coding the SBD Navigator and thus have been displayed in Figure 31-2. The five stars rating option (see Figure 31-2) gives an opportunity to system designers to select the most applicable design tools and methods in particular design projects. In this way the recommendations of the best tools to be used are shapped by the users themselves and thus the tool becomes an interactive IT platform for system designers' collaboration while working on their projects. By clicking on the hyperlink of the invdividual tool, a short description pops up explaining the main principles and the area of application of each individual tool, as shown in Figure 24.

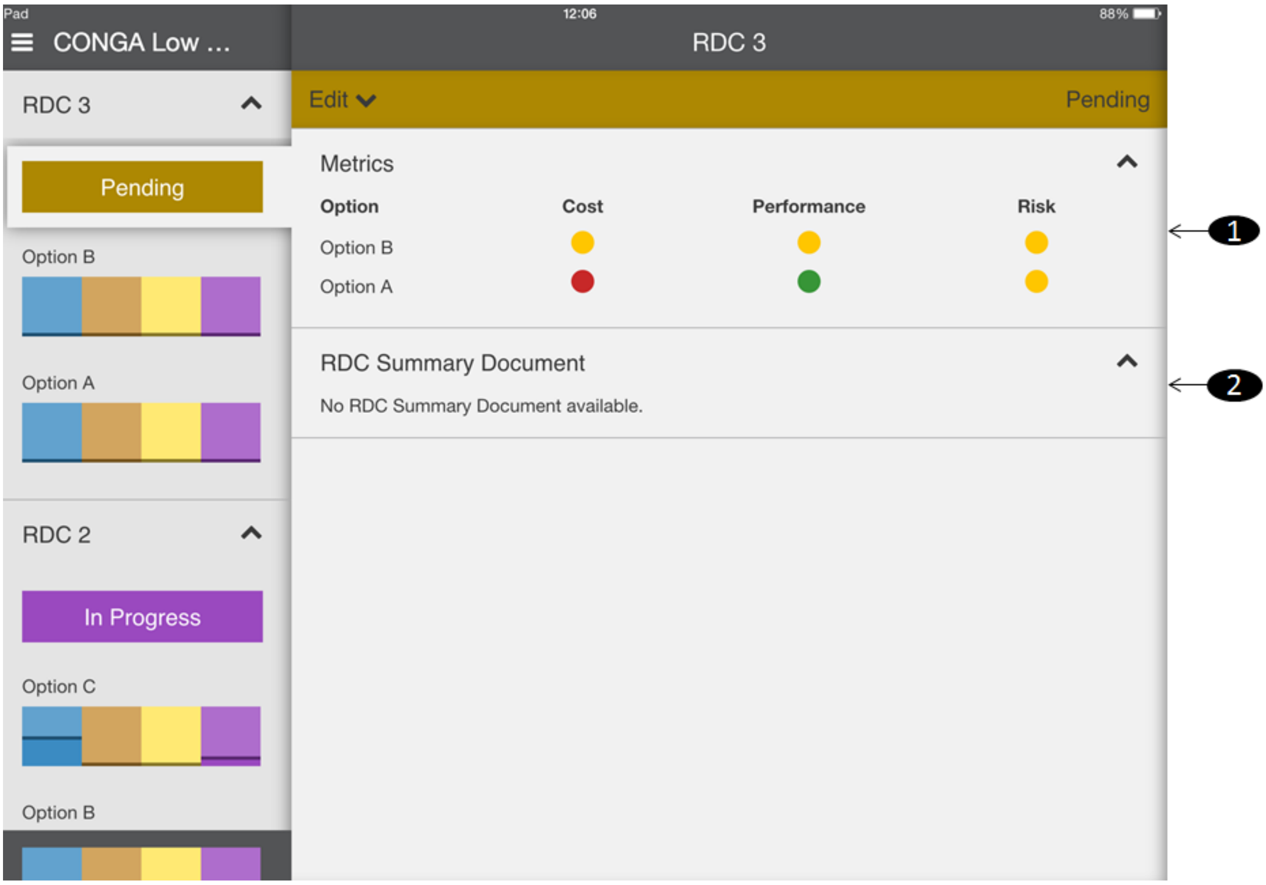

Figure 312: Comparison of metrics of different design options within SBD Navigator

Figure 32 presents metrics comparison capability of the SBD Navigator (Figure 32-1). Basically, the tool lists a few different design solutions and assesses them by evaluating the maturity of each under certain criteria. This maturity of the metrics is mainly adjusted by the technical lead. This functionality is activated by selecting one of the RDC maturity tabs (Figure 31-3). Each of the RDCs display one of three different maturity levels possible – 'In progress', 'Pending' and 'Completed'. The metrics section adopts traffic light principles using green, yellow, and red colour code to assess the completeness/maturity of the different parameters.

By comparing different solutions under 'cost', 'performance' and 'risk' criteria it makes it easier to decide which of the solutions is the most optimised and how long it could take to progress the solution further. It has been decided to incorporate more metrics into the future itterations of the SBD Navigator in order to expand the expertise of the design solution parameters being displayed.

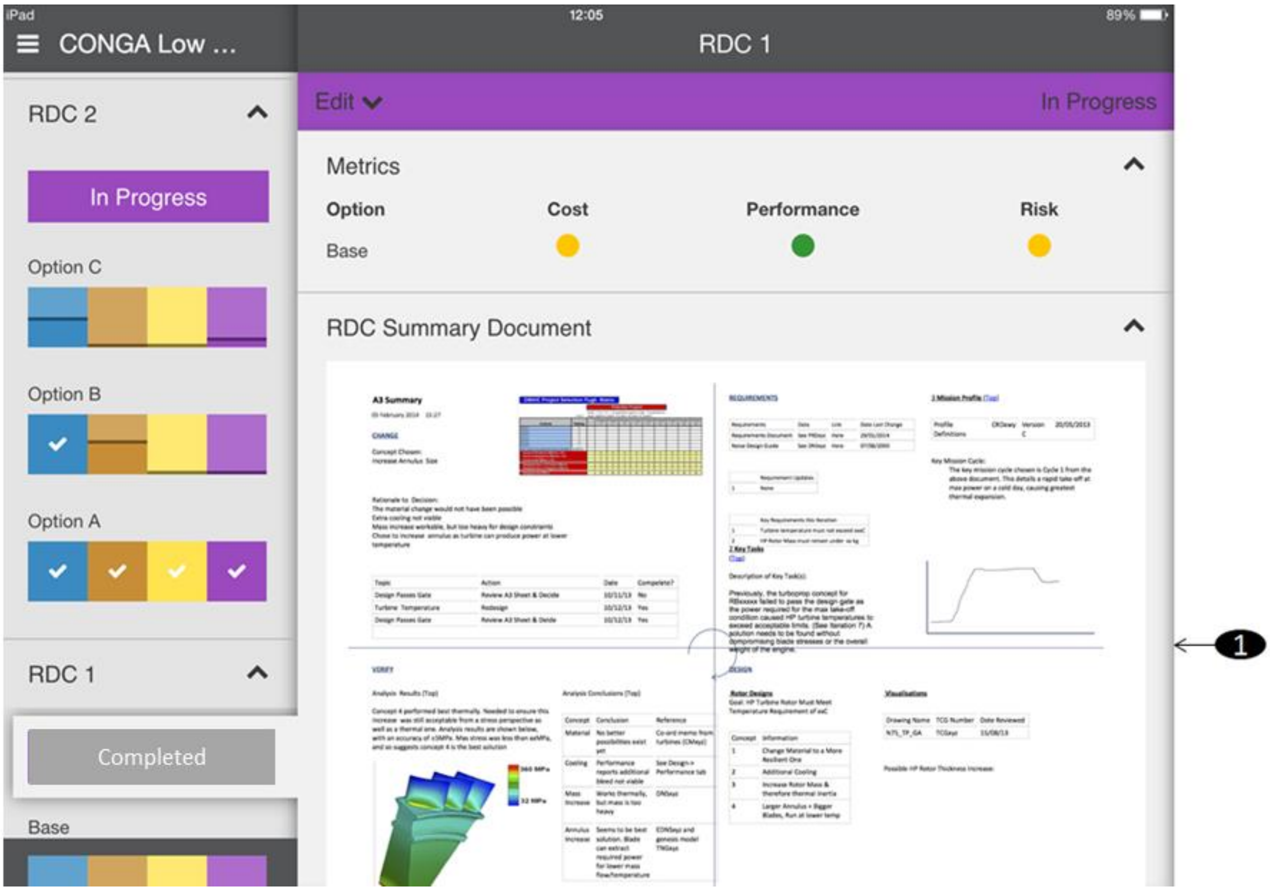

Figure 323: RDC Summary Document within SBD Navigator

Figure 33 presents RDC summary document (33-1) that is produced by the SBD Navigator after the completion of all four phases of the particular RDC cycle. It is activated by clicking the arrow of the 'RDC Summary Document' (32-2). The aim of this summary is to split the RDC into four main phases – understand, design, make and verify, - and to present the outputs from each of them in one single document. These outputs allow analysing the rationale behind the decisions taken during the progress of the design. The document is presented at the SDR meeting enabling to present the design space analysed (at the end of the SDR0) or a solution(s) selected (at the end of SDR1). It lists the results of the comparison of the metrics highlighting different optimum solutions under various criteria selected.

6. SBD NAVIGATOR VALIDATION

6.1 The initial SBD Navigator feedback from the potential users

In order to assess how successfully the SBD Navigator presented the enhanced SBD process model it was decided to ask potential end users to review and advice the research team by allowing them to try the tool for a few days following the open questionnaire to be answered. The tool contained a low noise engine use case preloaded as a possible scenario for the collaborative perspective design work. The questions covered mainly SBD Navigator's main functionality effectiveness and the possible layout topics, as shown in Figure 34:

SBD Navigator questionnaire / feedback form

1. Do you find the SBD Navigator easy to use without a manual? Comments, if any.
2. Do you like the layout of the software? Comments, if any.
3. Do you agree with Robust Design Cycles and their stages - RDC1, RDC2, RDC3, Understand, Design, Verify and Change? Comments, if any.
4. Do you find that the colour code applied easies the navigation? Comments, if any.
5. Do you find the measurement of the completeness of the project useful? Do you like the layout of the software? Comments, if any.
6. Do you find it useful to browse vertical slices of the project and would you find it useful to browse horizontal slices for each step? Comments, if any

   Additional info:

   Horizontal Slice – view and compare the same process step across several options, families and projects.
   Vertical Slice – view and compare the evolution of the design at a particular stage

in the RDC e.g. evolution of requirements.

7. Do you agree with main internal regulations added to the main page? Comments, if any.
8. Do you agree that the software should be viewable from different roles perspective? Comments, if any.
9. Do you agree that PD tools and methods used at each design step should be ranked by the user? Should it be a compulsory activity? Comments, if any.
10. Do you find the integration with a notes capture system beneficial? Comments, if any.
11. What sort of data would you like to be captured in the step output section of the navigator, e.g. project drawings, diagrams etc. Comments, if any.
12. Do you agree that the step output section and RDC summary section could be used at the design review instead of the normal PowerPoint presentation? Comments, if any.
13. What extra functionality would you like to add to it if possible? Comments, if any.
14. Would the Mobile version of the Navigator provide additional benefit?
15. Is the time taken to access summary data important to you?

Figure 334: Questionnaire for the SBD Navigator validation

Eight system designers were chosen from various departments within the company. The main goal was to gather the feedback from people who had different levels of experience within systems design and who could look at the tool and its functionality from various perspectives. Even though the tool was covering system level design work it was obvious that the complexity of the navigation was present and so it was necessary to evaluate the SBD Navigator from different users' perspective. This way of gathering the feedback (from different views/experience level perspectives) is effective due to the ability to address majority of the possible deficiency within the IT solution and the process model it follows. The results were analysed by the expert from the collaborative industrial company and the research team.

The tool was introduced to each of the participants individually by explaining the functionality and the evolution of the tool for 20-30 minutes. A short manual was sent to all participants of the validation process that explained the new concepts and briefly reminded of the aim and the functions of the SBD Navigator. Each participant kept the SBD Navigator for approx. 1 week. The questionnaire contained 15 questions with an ability to add extra comments, if needed (a mix of open-ended and close-ended questions; questions with possible multiple answers were avoided in order not to limit the answers of the participants to the scope of the question).

The answers and suggestions were combined into a joint picture of the changes required, by creating a table, as shown in Figure 35:

Requirement for the second iteration (combined – from 8 system designers (potential users of the product)	Rationale	Comment	Needs action/ No action
Answer: 1.The SBD Navigator should have a manual or a landing page explaining basic functionality and concepts with explanations of RDC and SBD and alignment with DDRAM / SDR / PILM	Quicker/easier navigation	Consider what terms need explanation	Yes
Suggestion: A new user should be able to operate the Navigator without the need to refer to a user manual. Consider "at point of use" instruction of some of the features			
Answer: 2.The SBD Navigator should consider using a project related icon for the projects rather than a tool-box style / The SBD Navigator should highlight that checklists are not mandatory	Might help to clarify the purpose of the left hand navigation section / company's politics to move away from		Yes

	checklists and gates		
<u>Suggestion:</u> Consider replacing Check list with Prompt List			
<u>Answer:</u> 3.The SBD Navigator should explain RDC completeness requirements / combine certain steps of initial RDC phases	Confusion over SDR gates clarification / ease navigation by avoiding duplication	Same as req 1	Yes
<u>Suggestion:</u> It should be clear at what RDC the final choice of design concept that will be embodied into the product will be reached.			
<u>Suggestion:</u> It should be possible to tailored to the different RDC cycles			
<u>Suggestion:</u> Duplication of steps between different concepts options should be available		Important req/needs addressing	Yes
<u>Suggestion:</u> When you go through a DR gate with multiple concepts, only certain parts of the DR gate would need to be repeated		Same as req above	yes
<u>Answer:</u> 4.The RDC should consider fully colour blind people issue		Achieved	No
<u>Suggestion:</u> The graphics should consider people with less than perfect eyesight e.g. able to zoom in on some images and graphs to gain additional clarity		Achieved	No

Answer: 5. No extra req		Achieved	No
Suggestion: The user should be able to save multiple projects within the same software		Achieved	No
Suggestion: The Navigator should be able to display a comparison of progress between two or more options within a project		Achieved	No
Suggestion: The Navigator should be able to display a comparison of progress between two or more projects		Not achieved	Yes
Suggestion: The Navigator should give prompt to provide evidence when checking off tasks		Not achieved	Yes
Answer: 6. The SBD Navigator should enable browsing of vertical slices of the project and browsing horizontal slices for each step	Quicker comparison tasks		
Answer: 7. The SBD Navigator should link to SE tool guide	Eliminate out of date data possibility	already planned	yes
Suggestion: Mandatory Work Instructions needs to be dynamic and auto-update		already planned	yes
Answer: 8. The SBD Navigator should be viewed from only one role perspective (systems designer's)	Simplicity	N/A	No
Suggestion: It is essential that different roles are implemented		N/A	No
Answer: 9. Tools should to be categorised into systems design / engineering and software tools; The SBD Navigator should have comments box for rating preferences	Different design circumstances may affect rating	req important - add feedback option to OneNote tool	Yes
Suggestion: The user should be able to add tool comments and examples		Same as previous	Yes

Suggestion: The Navigator should have the ability to set different Tool Star ratings for different RDCs		Achieved	No
Answer: 10.The notes capture should be an imperative task	Software would become an interactive checklist otherwise	req important	yes
Suggestion: The notes capture should not be an imperative task because. The existing DR gate system would be rather modified.		same as above	Yes
Suggestion: The Navigator should create output templates with data added e.g. generate 4-box charts		N/A(designer would create 4 box chart on OneNote)	No
Answer: 11. The SBD Navigator should display drawings, performance data, charts, presentations, models (viewable/interactive), videos, photos, graphs, spreadsheets viewable vs The SBD Navigator should link to the OneNote only		n/a (snapshots of any format can be used)	No
Suggestion: Data should be kept in linked DR data packs		n/a	No
Answer: 12. No extra req		n/a	No
Answer: 13. Linking options should be added between 'understand' step for different concepts. Project matrix should be added to see how well the design options are meeting customer requirements	Avoid duplication of same steps within phases	same as req 3	No
Suggestion: The tool should become a point of index for projects		n/a	No
Suggestion: The Navigator should create a live Pugh matrix		n/a unless created on	No

		OneNote	
Suggestion: It would be useful to display the project progress on the navigator page (on the right) when the project is first selected or reflect progress in the colour bar at the bottom of the step selection toolbar		req important	yes
Suggestion: A need to capture specific actions raised during design reviews		N/a OneNote to be used	no
Suggestion: A need to display more specific data about product attributes		n/a	no
Suggestion: Add "Patent Search" to the recommended tools and methods section under existing product design		req important	yes
Suggestion: Add links to the lists of company engineering fellows		n/a	No
Suggestion: Add tools to: Analysed Design Space (RDC1) This is a really big aspect of the design task. Function Means analysis is a means of capturing alternative design concepts through correlation with system functionality. Suggest adding reference to this in tools and methods. DRED should be used to capture rationale behind design options and would be useful in this stage of the design. CAD (NX) is also a tool that is useful to identify geometric design space in a similar way to genesis. Maybe it is too early at this stage but we should be considering how we are going to perform concept selection using tools such as Pugh matrices.		n/a unless created on OneNote	No
Suggestion: Remove Infeasible Regions step		req important (join 2 steps into 1)	yes
Answer: 14. No req		n/a	no

<u>Answer</u>: 15. Additional metrics should be added instead of having current three attributes	Three attributes are not sufficient to make comparison	n/a (too complex, these could be covered in an A3 sheet)	no

Figure 345: Questionnaire answers and suggested changes for the SBD Navigator

A new list of requirements for the 2nd iteration of the SBD Navigator software followed shortly after analysing the feedback and suggestions given by the system designers. Due to the researcher's limited involvement into the further process of upgrading the SBD Navigator, the exact list with detailed requirements cannot be revealed.

6.2 The second iteration of the SBD Navigator

The main areas of changes required were split into two main sections:

- The visual layout improvement
- Changes of the functionality

The key concerns regarding the layout improvement: the system designers found it difficult to use the SBD Navigator without a landing page or a manual that would explain basic functionality and new concepts with explanations of the RDC, SBD and alignment with DDRAM / SDR / PILM, - question nr 1 (see Figure 34), the answers and suggestions are shown in Figure 36. It was obvious that a need for an extra clarification of the enhanced process model alignment to the old process model was present. In high complexity companies like Rolls-Royce, there are usually a few process models running in parallel in order to present the main goals of design, engineering, marketing and business teams. The enhanced RR-SBD collaborative perspective process model brought in new concepts like RDCs and SBD which was the reason for the system designers to ask for some extra explanation, especially for the first time users of the tool.

The other changes referred to altering symbols of the icons to show project based perspective possibilities. Another suggestion invoked to a better empowerment of the

SBD by displaying snapshots of all design options at the end of the RDC. The purpose of this functionality was to enable the comparison of various design options and also to enable the analysis of the design rationale behind the process of narrowing down the sets of solutions in order to select the optimum design option that would best satisfy stakeholders' requirements. Another request related to an incorporation of a 'work in progress' data that could be reviewed on daily basis to assist the decision making process. A Microsoft Office OneNote application was selected as the best tool to enable this functionality.

The key concerns regarding the software functionality: the system designers offered to reduce the complexity of the steps displaying the requirements by joining them at the lowest level of the RDC for the same type of design solutions (see question 13 – Figure 34, see answer 13 – Figure 35). The aim was not to duplicate the requirements for the solutions that were developed under the same set of requirements. It was offered only to refer these design options to certain steps of the RDC, adding a note that the requirements were identical. According to system designers, it would enable a better concentration on analysis of the design solutions in parallel.

Another important feedback/suggestion covered role view perspective functionality. System designers offered to view the design data on the software only from the system designer's perspective eliminating two other options (initially it was planned to make the tool viewable from the process manager and the technical lead perspectives additionally). This functionality simplification is being discussed by the company. The other important feature of the software functionality referred to additional metrics to be added rather than having just three attributes that would enable the comparison of the parameters of the design sets to a fuller extent (see question 15 - Figure 34, see answer 15 – Figure 35).

6.3 Key findings from the case study

It was very important to find the weakest points of the SBD Navigator that could have been addressed during the creation of the 2nd iteration of the software: this particular research was mostly concerned with the analysis of the design tools that enable SBD and their application at a system level PD preliminary design phase by using a computerized tool – the SBD Navigator. As advised by the potential users of the SBD process model, while reviewing the SBD Navigator, even though Rolls-Royce does exercise SBD, the issues occur in design options down-selection phase. The design participants tend to narrow down the design solutions based on their experience in previous projects. The presented functionality of the SBD Navigator should encourage to dowselect the design solutions as the design progresses by analyzing them in parallel. Figure 33 presenting the metrics comparison capability enables to assess the maturity of the different design options under various criteria. Figure 33 displays the RDC summary document that covers the design rationale behind the donwselection process of the particular project.

Another issue was related to a non-existence of a systematic way of recording the results of the analysis of the design sets and the decision making rationale. Figure 30 presents the ability to save snapshots of the data being analyzed and to share it among the team members. As system designers tend to reject certain design options based on their previous experience and their expertise in engineering field rather than on design analysis and testing, the justification and proof of their decision making is lost. The SBD process model encourages the exploration of design options and the down-selection of these options only if certain design activities have been completed, for example – simulation, testing, prototyping or modelling of the system. It doesn't mean that the systems (prototypes) have to be actually built. The aim of the SBD is to record the results of the simulated/real design data for future design work. This data can be further progressed by other design teams when the right time comes, for example TRL (technology readiness levels) may not be at the required maturity level to progress the new technology as yet. If some analysis of the system performance is generated of the possible solution it can be re-used in a few years' time, when the TRL is at the required level. Such way of developing new products improves company's competitiveness due to a much shorter response timescales to the customer.

7. CONCLUSION AND FUTURE WORK

This research was qualitative, and adopted various research methods approach defined in chapter 1. This study is structured out of main three phases: the literature review about PD, SBCE/SBD; the analysis of current SBD practice within Rolls-Royce; and the proposal how to create an effective software platform guiding potential users via the enhanced Set-Based preliminary design phase. The author tested the proposed solution using a low noise engine case study, as presented in chapter 6. The feedback given by potential end users enabled to evaluate the proposed solution and to add additional features to the SBD Navigator in order to meet the desired functionality of the tool. The agile way of altering the software code has been discussed in chapter 5, which enables effective and fast adjustment of the code when needed by involving the software developer, potential users and the experts from the industrial partner company into the software development process.

7.1 The adopted Research Methodology

A systematic literature review enabled to analyse the key features of the SBCE/SBD process model and to identify research gaps that included the absence of an IT independent platform tool that could guide potential end users via the enhanced process model. As a result the case study focused on testing the initial version of the SBD Navigator in a real engine data environment. By combining theoretical and contextual analysis of the enhanced SBD process model and the feedback given for the SBD Navigator a modification plan of an improved version of the tool was developed.

7.2 The fulfilment of the Research Aim and Objectives

The aim of this research was to enhance the existing SBD process model and to assist the development of a SBD Navigator which would take system designers through the proposed design steps in preliminary design phase. The logic of the improved SBD process model has been presented in chapters 3 and 4. The SBD Navigator logic and its architecture are presented in chapter 5.

7.3 Key research contribution

The research presented contributes to human knowledge in a few ways:

1. A detail analysis of the design tools and methods (Chapter 4, figure 25)
2. Researcher leading the work of the tools definition during the evolution of the SBD process models, specifically focusing on the final version, shown in figure 22.
3. The design and the usage of the IT architecture of the SBD Navigator.
4. The constant enhancement of the process model and the software, guiding the end users, based on the collaborative communication between the stakeholders.

7.4 Possible future work

Based on main findings from this research a few suggestions could be put forwards for further research:

Firstly, it is recommended that the SBD process model is tested through further usage of the SBD Navigator. The feedback given by the end users is expected to produce various benefits which will help to refine the SBD process model further.

Secondly, this research is required to extend the application of the SBD principles to lower levels of the product design covering subsystem and component level design work as well as to detailed design phase and the rest of the product lifecycle.

Thirdly, this research could benefit out of analysing and testing alternative IT platforms for the SBD Navigation tool.

7.5 Conclusions

1. The SBD is an important approach in improving the PD process of any company. However, it requires a clear process to follow and a set of tools and methods to enable the activities within the process model.
2. The integration of the SBD principles into the current PD of any company needs to be addressed in a smooth manner by adopting and using the right language and the sequence of the activities and the associated tools.
3. There are many design tools and methods that could support different PD activities, but it is important to have a detailed study of them and to evaluate how suitable these tools and methods are for selecting the different PD activities.
4. The logic behind the selection of the design tools and methods should not only rely on the theory and the principles of the PD tools and methods but rather on the tangible experience of different designers and engineers.
5. A development of a detailed and customised SBD process model is not enough. Any process model requires a guide how to follow it. Complex process models like SBD best benefit out of a platform independent software guiding and navigating the end user.
6. In order to address the possible complexity of using the SBD Navigator the most appropriate approach is to develop an easy adjustable, self-explanatory and interactive tool compactible with various IT platforms.
7. Feedback received from potential users' highlighted deficiency of some of the functionality of the SBD Navigator which results in the need to update and iterate the tool as often as the requirements from the stakeholders involved come through.

Complex products result in the need of a higher complexity design tools to be developed that enable a fault-free product design in desired timescales by satisfying the requirements of the stakeholders involved in the design process. The effective products can be created only if research and industrial teams work in a collaborating environment advising each other. In this project the obvious advantage was that the agile development manner of the SBD Navigator was stimulated by the system designers (potential users) revising the tool and then advising the research team of the changes required (chapter 5).

How successfully the SBD Navigator is handling real design cases will be proved by real projects using the tool on daily basis. Different project scenarios (system level, subsystem or component) may need a major reconfiguration of the tool in order to meet the needs of the individual teams. It is very important to structure the hierarchy of the design tools and methods being used within the SBD environment. To satisfy this requirement the star rating option is being enhanced by the developer currently. The current work has been based on company's best practice and research findings however, some usage of the enhanced process model may reveal gaps within the new process model and result in the alteration of the logical selection of the design tools and methods in the SBD environment.

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