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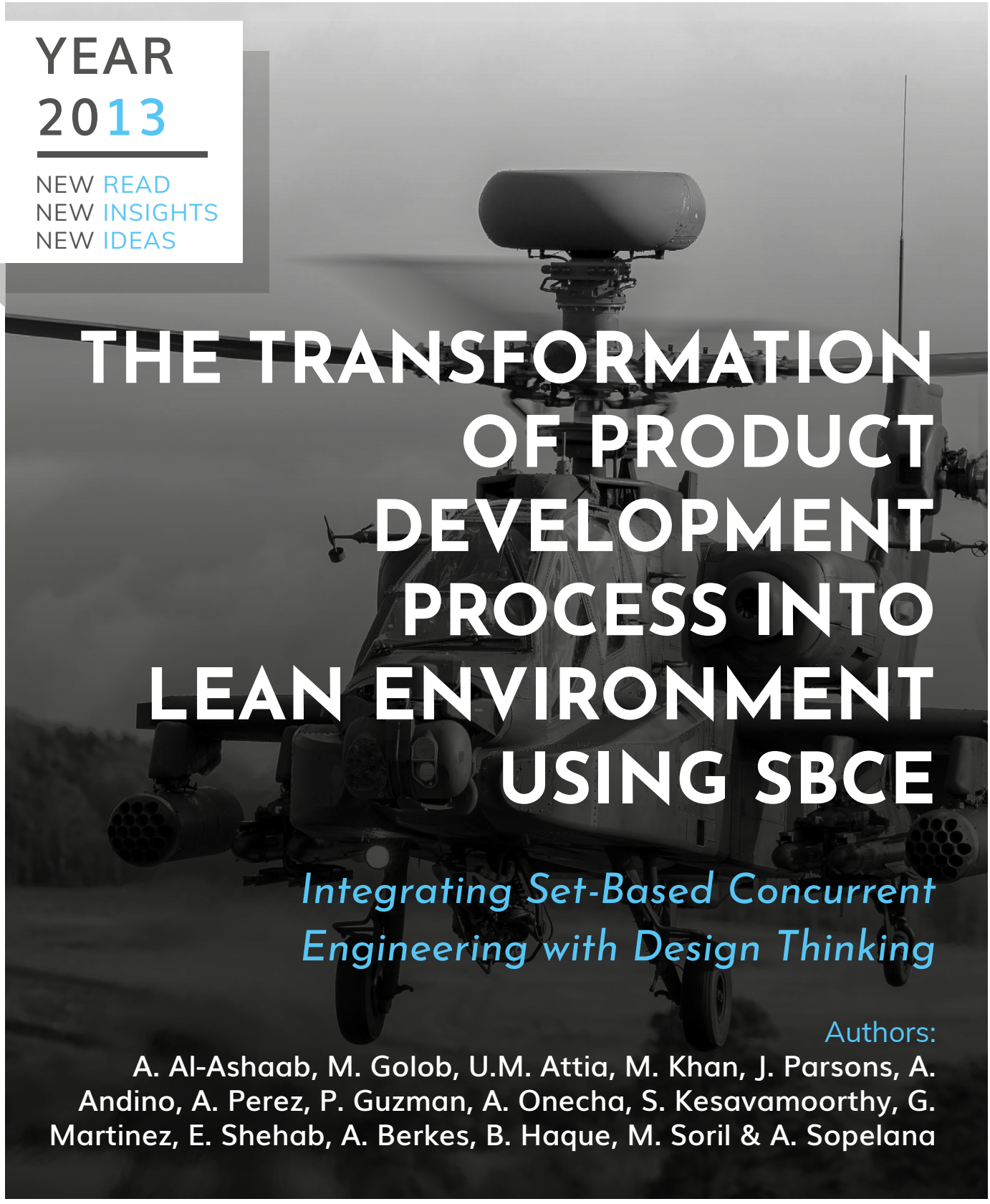

THE TRANSFORMATION OF PRODUCT DEVELOPMENT PROCESS INTO LEAN ENVIRONMENT USING SBCE

Integrating Set-Based Concurrent Engineering with Design Thinking

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The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry

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Abstract

This article presents a transformation process towards lean product development in an aerospace industry. This transformation was achieved in two main stages: the first was to integrate the principles of set-based concurrent engineering into an existing product development model of an aerospace company. This stage included defining activities and associated tools. The second stage was to implement the developed model in a research-based industrial case study, a helicopter engine in this case. Three main outcomes were realised from this work. First, it presented an industrial case of lean transformation in product development, where the leanness of an existing model was enhanced by embedding set-based concurrent engineering principles. Second, the developed model was structured into a set of well-defined activities and associated tools that were previously scattered or redundant. Finally, the developed model was trialled in an industrial project of a helicopter engine, tested to evaluate its value in enhancing the innovation level and reducing risk. The work presented in this article focused on early stage system level design, and future work will extend the implementation of set-based concurrent engineering to sub-system and component levels.

Keywords

Lean product and process development, set-based concurrent engineering, lean transformation, product development, aerospace

Introduction

The increasingly competitive economic environment puts pressure on organisations to produce new products, which means products with higher quality, lower costs and shorter lead times. This is because organisational survival and long-term growth depends on the introduction and development of new products. For decades, researchers have focused on defining principles and practices to increase effectiveness and efficiency of product development (PD). Among different PD approaches, lean PD was introduced in the early 1990s based on Toyota's Product Development System, enabling it to become a world leading car manufacturer (Womack et al., 1990). Since then, increasing research efforts have been directed towards defining and structuring lean PD as a general PD paradigm (Muffatto, 2009).

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This article presents an industrial case study in which a conventional PD process in an aerospace company has the potential to be transformed into lean PD by implementing the principles of set-based concurrent engineering (SBCE).

The rest of this introductory section comprises a review of the state-of-the-art in lean PD and SBCE. Section 'Research methodology' presents the research methodology. Section 'Developing the SBCE practices in the RR-LeanPD model' explains the activities of the new lean PD model and its associated tools. Section 'Application of the RR-LeanPD model on a helicopter engine' presents an industrial case study where the new model and its tools were implemented for a development project of a helicopter engine. In section 'Conclusion', the new model is assessed in the light of the case study results.

Lean PD

Lean PD has been influenced by a steady need for increased effectiveness and efficiency: the quicker introduction of better and less costly products (León and Farris, 2011). Elements of Toyota's Product Development System were presented briefly in the influential book *The Machine That Changed the World* (Womack, 1990). Toyota PD focuses on three elements: value, knowledge and improvement. This enabled the company to please customers through optimal designs, to minimise design rework and achieve high profit levels (Morgan and Liker, 2006).

While the Toyota Production System was thoroughly explained and documented by Ohno (1988) and others, the company's Product Development System has not been well defined or documented (Sobek et al., 1999; Ward et al., 1995; Womack et al., 1990). Researchers have, however, made good progress in developing the enablers of lean PD, and several approaches have been proposed to define how PD could become 'lean'. Reviews of research progress in lean PD during the past two decades can be found in the literature (Hoppmann et al., 2011; León and Farris, 2011; Khan et al., 2011b).

The authors have already developed a new lean PD model within a European project about lean product and process development (LeanPPD; Khan et al., (2011b)). A core enabler in the LeanPPD model is SBCE, which is discussed in the following section, and is the base for the presented case study.

SBCE

SBCE could be defined as the process where

> design participants practise SBCE 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)

Critical design decisions are deliberately delayed until the last possible moment to ensure that customer expectations are fully understood and that the reached design meets the requirements of different functions (design, manufacturing, etc.).

Ward et al. (1995) were the first to investigate Toyota's Product Development System, coining the term 'set-based concurrent engineering' to describe the approach, in contrast to the commonly known 'point-based' design approach (Prasad, 1996), where a single design is selected as early as possible in the design process, and a multi-disciplinary design effort based on this single solution until a satisfactory solution emerges. They summarised the procedure in the following steps:

1. Design team defines a set of solutions at the system level rather than a single solution.
2. It defines sets of possible solutions for various sub-systems.
3. It explores these possible sub-systems in parallel using analysis, design rules and experiments to characterise a set of possible solutions.
4. It uses the analysis to gradually narrow the sets, converging slowly towards a single solution.
5. Once the team establishes the single solution for any part of the design, it does not change it unless absolutely necessary.

Sobek et al. (1999) developed the five-step procedure of SBCE into a systematic framework comprising three main principles, each consisting of three stages, as follows:

1. 'Map the design space' is a principle that aims at achieving a thorough understanding of the set of design possibilities, also known as the design space.
2. 'Integrate by intersection' is a principle that ensures that design teams integrate sub-systems by identifying solutions that are workable for all functional groups.
3. 'Establish feasibility before commitment' is the principle of narrowing sets down to an optimum solution at the system level.

The above principles also detailed influential elements of Toyota's Product Design System that facilitate designing with sets of solutions. These components include the roles of the chief engineer, different

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communication tools (such as checklists, A3 forms and design matrices), in addition to the value of knowledge and expertise in the design system.

Morgan and Liker (2006) expanded the six mechanisms of Toyota PD into a lean PD conceptual model based on a sociotechnical system consisting of three primary interrelated and interdependent sub-systems: process, people and tools and technology. Each sub-system consists of a number of principles, which add up to a total of 13 principles that describe the Toyota PD.

Ward (2007) defined concrete steps of set-based design, including classifying projects, breaking systems into the smallest feasible pieces, defining targets for system and sub-systems, generating multiple concepts, filtering multiple solutions by aggressive evaluations, mapping feasible design space and converging towards the optimum solution. Inoue et al. (2010) developed a software based system to assist in handling uncertainties based on the preference set-based design method (Nahm and Ishikawa, 2005) to support the decision-making in PD. Kennedy et al. (2008) considered SBCE as the one of the main cornerstones of LeanPD.

SBCE within the LeanPPD model

As part of the LeanPPD European project, Al-Ashaab et al. (2010) and Khan (2012) developed a new model based on lean thinking, which considers the entire product life cycle. The LeanPPD model consists of five key enablers: value, knowledge (or learning), continuous improvement, chief engineer and SBCE, which is the core enabler. Khan et al. (2011b) outlined the SBCE approach in five main principles, as shown in Figure 1.

The main outcomes of the five 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 sub-system 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 sub-system 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

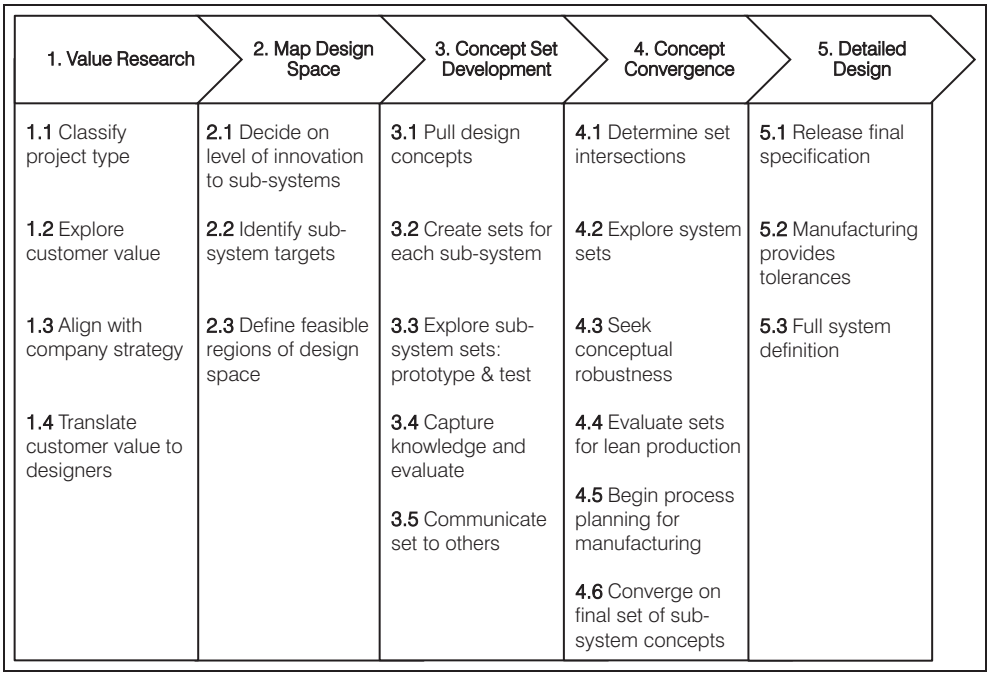

Figure 1. SBCE process and activities within the LeanPPD model.
SBCE: set-based concurrent engineering; LeanPPD: lean product and process development.

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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.

Advantages of SBCE

SBCE has a number of advantages compared to conventional point-based approaches. These could be summarised as shown below (Kennedy, 2008; Khan et al., 2011b; Raudberget, 2010; Sobek et al., 1998; Ward et al., 1995):

1. Avoidance of costly reworks in later design stages.
2. Reaching optimum solutions by ensuring that all functions are involved in the design process simultaneously, and all the alternative solutions fall within the intersection of these functions.
3. Efficient communication where the whole set of possible solutions is described and where earlier communications are still valid but become more detailed and precise.
4. Innovation and creativity are enabled by set-based solutions, flexible designs, delayed decisions and gradual convergence.
5. Organisational knowledge and learning is promoted by capturing, sharing and implementing the knowledge produced throughout the entire PD process.
6. Risk of failure is reduced because of the considerable number of generated solutions.

Challenges and research gaps in SBCE

As explained in the previous section, SBCE proves to be a promising PD approach with several potential benefits over conventional design approaches. However, a number of obstacles need to be overcome before SBCE could become a standard practice in lean PD.

The first obstacle is the lack of a clear and structured SBCE model. As shown earlier in the literature review, SBCE is usually presented as a set of generic descriptive principles. There is still a need for a structured SBCE model with a clear set of activities that allows a lean PD process. As shown in Figure 1, the LeanPPD project is already tackling this challenge. The second challenge is the lack of clear guidelines for how to implement SBCE in practice. The need exists for a step-by-step guide to enable designers to progress with sets of solutions throughout the PD process, indicating what tools to use for each activity. Another research gap is the limited number and variety of case studies where SBCE is implemented in industry. In addition to the original Toyota case study, little research exists concerning industrial applications of SBCE. This dearth of actual case studies makes design professionals in industry reluctant to implement SBCE, even if they like the idea (Khan et al., 2011a).

Research methodology

The methodology followed to address the challenges highlighted in section 'Challenges and research gaps in SBCE' consisted of three main stages: model development, defining tools and implementation. The model development stage focused on understanding the state-of-the-art PD model implemented at Rolls-Royce at the system level, which is known as the System Design and Integration (SD&I) model. SBCE practices were incorporated into the SD&I model in order to transform it into a lean PD model. The main outcome of this stage was an improved model entitled the RR-LeanPD model. The tool definition stage aimed to define the set of tools that would enable the implementation of the new model. The implementation stage focused on the case study, in which the newly developed RR-LeanPD model was applied to a helicopter engine project. The main outcome of this stage was a set of alternative solutions in addition to the captured knowledge and expertise.

Developing the SBCE practices in the RR-LeanPD model

This article reports on a case study where the developed SBCE model, shown in Figure 1, was trialled at Rolls-Royce, as an example of an aerospace industry, to transform the PD process into lean environment. The new model, referred to in this article as RR-LeanPD, incorporates SBCE principles defined by the LeanPPD model (Khan et al., 2011b). The activities and associated tools are structured and detailed. The new model is assessed using a helicopter engine design case study. The presented research work discusses how the company can integrate the principles of SBCE within its own PD process as a step towards lean transformation in PD, and how this step can influence the PD process.

SD&I, which is the current PD model at Rolls-Royce (shown in Figure 2), covers the whole design cycle of the product. It is divided into three levels: system level, sub-system level and component level. Each level has a set of activities, the output of which generates documents to be reviewed at the process gates,

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which, at the system level, are known as system design reviews (SDR0, SDR1, etc.).

Three main areas of improvement were identified as required in the SD&I model. First, 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. Second, although the SD&I 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 latest stages of development due to changing requirements related to development and certification. Such design iteration required considerable resources.

These three challenges were addressed by transforming the SD&I model shown in Figure 2 into lean environment using SBCE principles as defined in the LeanPPD project to produce the new RR-LeanPD model. This transformation process was implemented for the first two design review stages on the system level (SDR0 and SDR1). SDR0 is concerned with top level system requirements, and it aims at defining 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. The next sections present the model activities and the corresponding tools and enablers.

RR-LeanPD model for SDR0

Figure 3 presents the activity view and the corresponding 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 SD&I, while others were integrated from the SBCE.

Activities and corresponding tools are classified into five main groups, A–E, which correspond to the first stage of the SBCE model '1. Define Value', and its four sub-activities (1.1–1.4) shown in Figure 1. The tool selection for the activities followed an extensive literature review and consultation with the expert at

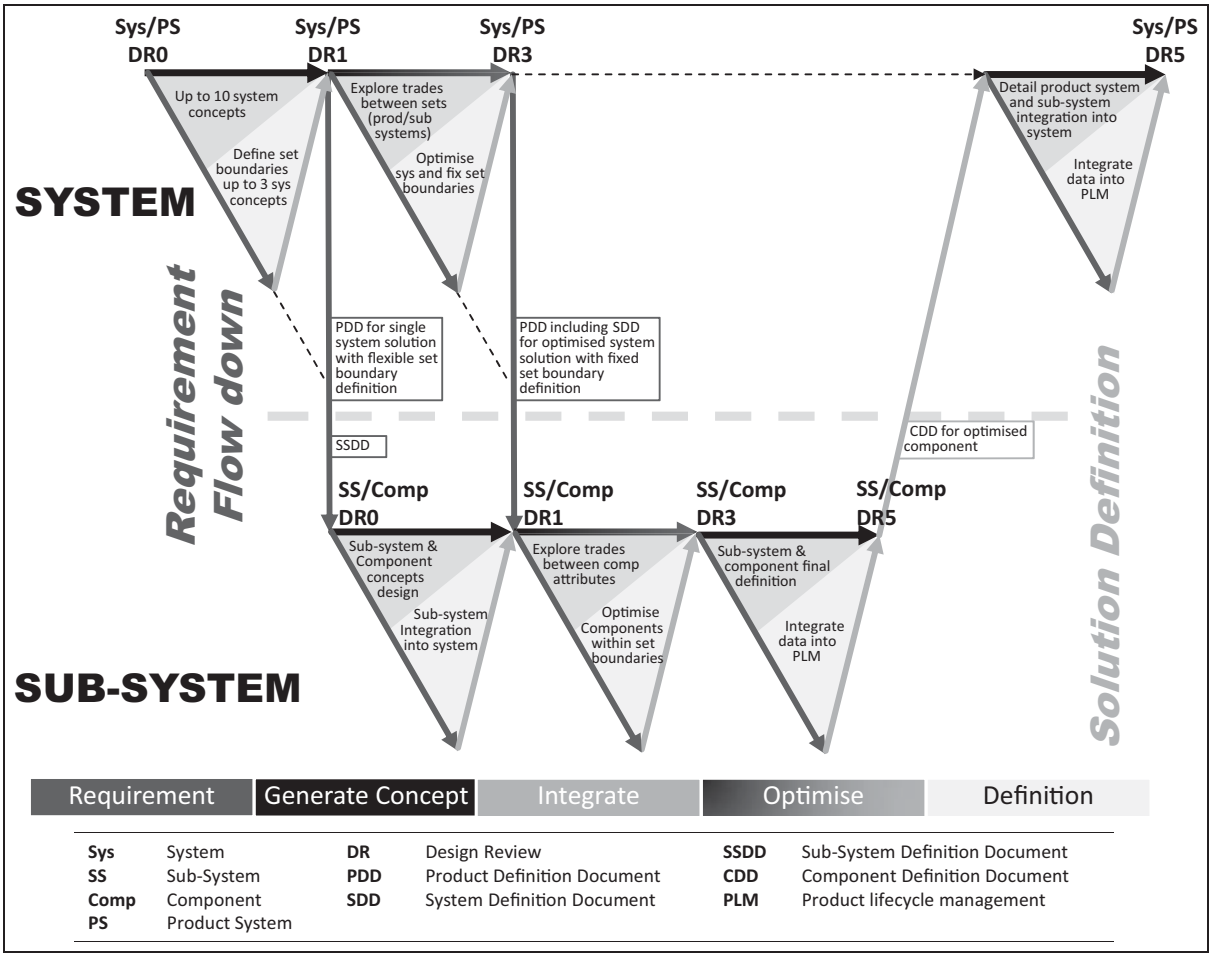

Figure 2. A simplified, two-level representation of the System Design and Integration model.

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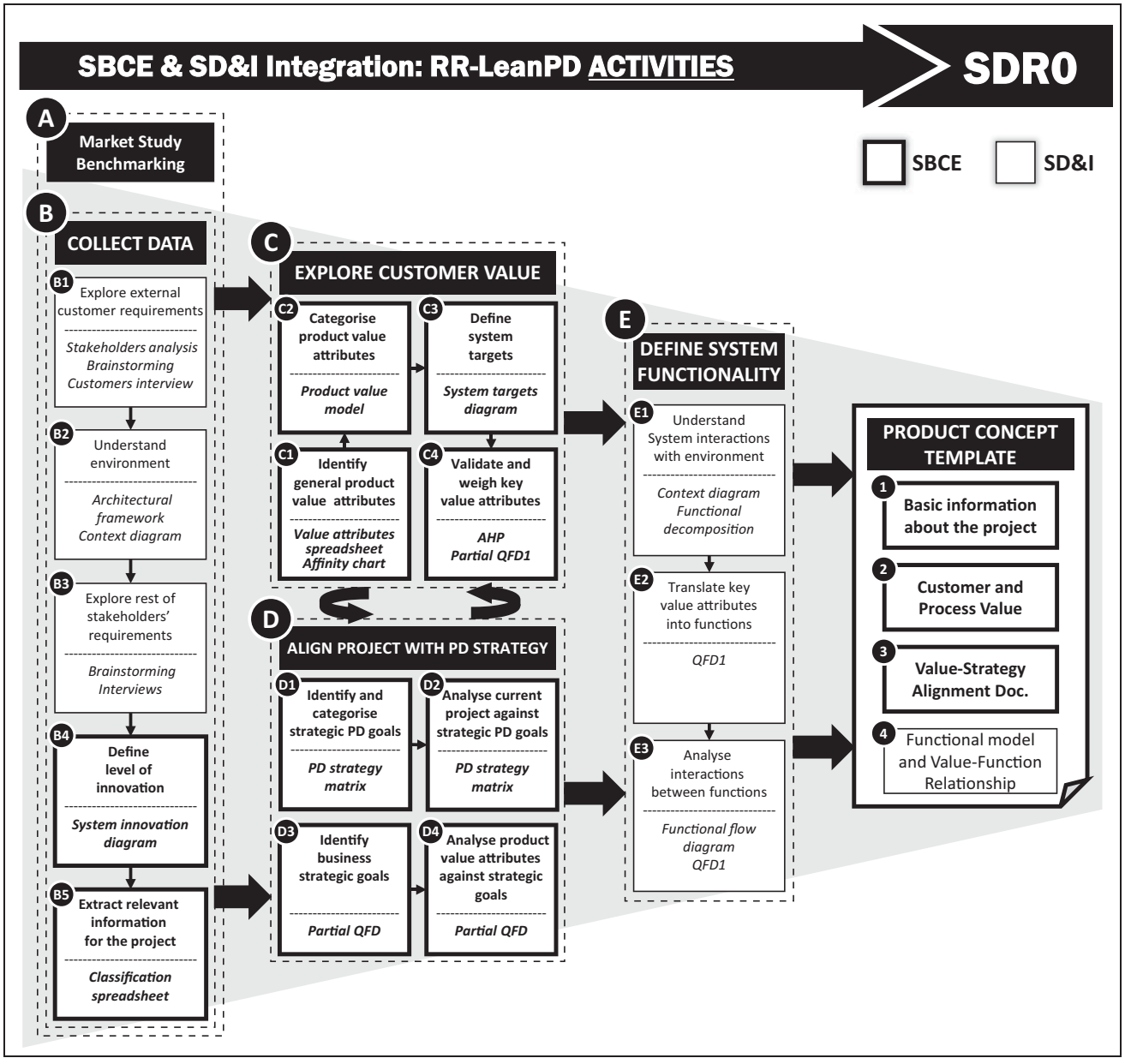

Figure 3. The RR-LeanPD model showing the activities and corresponding tools to reach SDR0.
SDR: system design review; SBCE: set-based concurrent engineering; SD&I: System Design and Integration.

Rolls-Royce as well as ensuring that the tool enables the implementation of SBCE principles. The following list outlines the activities in Figure 3.

Activities A – market study and benchmarking. It aims at understanding the market environment in which the project is located.
Activities B – collect data. It aims at combining 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 and B5 have been integrated into the SD&I 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 1 and aims at thoroughly understanding the customer value, which is an important prerequisite for defining system targets and assessing

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the leanness of alternative designs. 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 1. It aims at defining 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 additions to the existing SD&I model because they transform the PD process into a lean process in two ways: first, the customer value is thoroughly investigated and put at the centre of the PD process, and second, the key value attributes are aligned with the company's strategy. Both activities serve towards value creation, which is the essence of LeanPPD, as explained in section 'SBCE within the LeanPPD model'.

Activity E – defining system functionality. Activity E, which was already part of the original SD&I 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 interaction between each other.

Product Concept Template. The outcome of Activities A–E is documented here, which aims at thoroughly translating the customer value to design engineers. The Product Concept Template was integrated in the new model because the original SD&I 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.

RR-LeanPD model for SDR1

Figure 4 presents the activities and toolset of the second PD stage of the RR-LeanPD model, respectively, 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 1. Activity F, which is 'define architecture and establish targets', starts from where functional requirements were delivered in 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 1, where the level of innovation of each sub-system is decided using an innovation diagram. As the level of innovation in sub-systems increases, the number of solution sets is likely to increase, as will be shown later in the case study. 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 1. This is considered as a crucial stage for the success of the PD. This activity aims to identify the feasible regions of design space (i.e. what can, may, should, must or must not be done) which corresponds to activity 2.3 in Figure 1 and to extract and develop alternative sub-system design solutions which correspond to activities 3.1 and 3.2 in Figure 1.

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 sub-activity aims to graphically present and communicate the set of alternative system solutions which corresponds to SBCE activity '3.5: Communicate set to others' in Figure 1.

System Concept Template. Communication takes place in the form of a template, known as the System Concept Template, which is proposed to be the standard method to pass the information to the sub-system teams. 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 that the key value attributes identified at the SDR0 are actually met. The idea behind this 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 value definition is thoroughly communicated.

Application of the RR-LeanPD model on a helicopter engine

This section discusses a case study in which the newly developed RR-LeanPD model was implemented at

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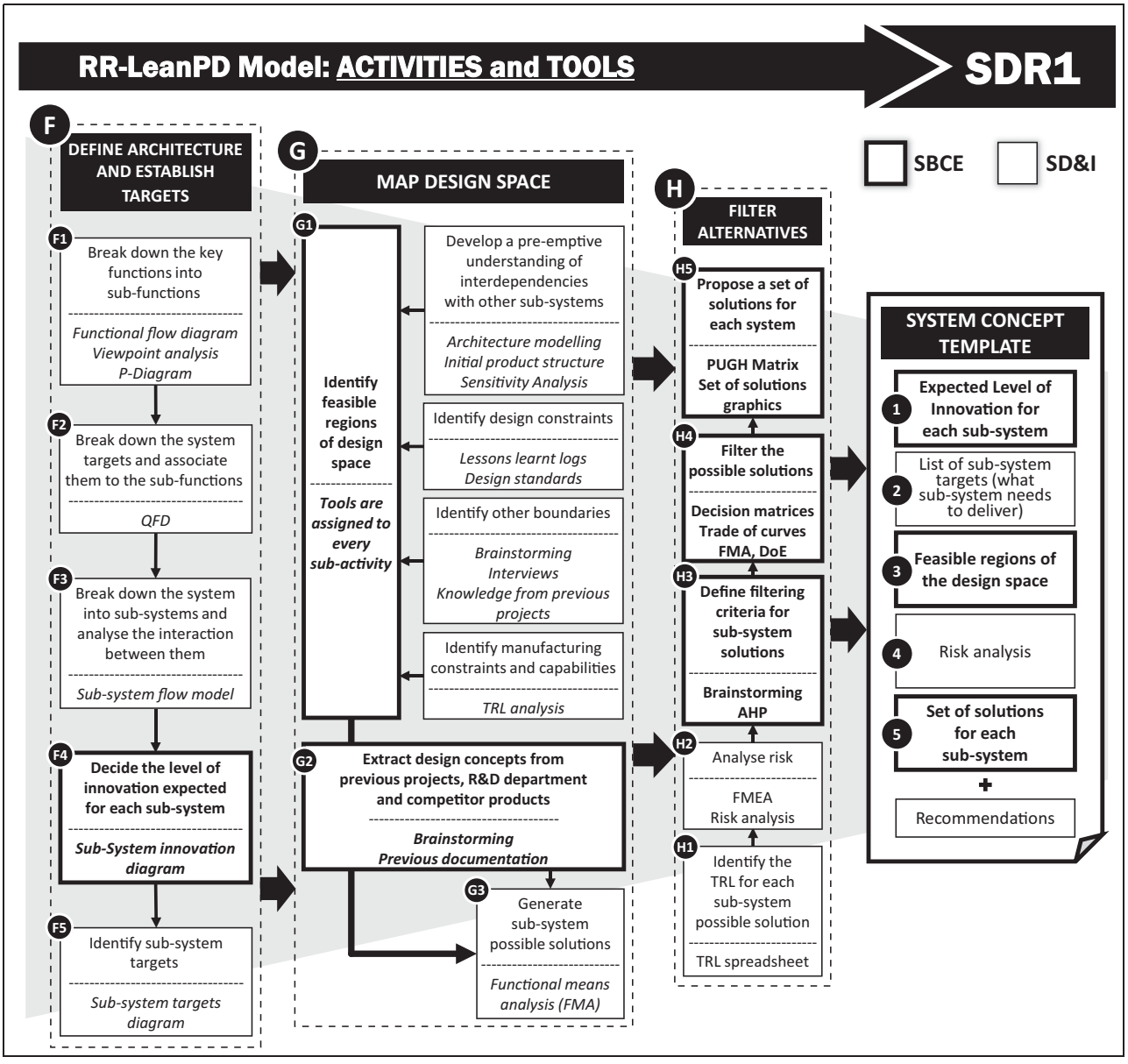

Figure 4. The RR-LeanPD model showing the activities and corresponding tools to reach SDR1.
SDR: system design review.

Rolls-Royce in PD project for a helicopter engine. The aim was to validate the model for the first two design stages and assess the industrial implementation of SBCE principles in a relatively large and complex system. In this research-based industrial case study, a PD team was formed from Cranfield University's researchers based full time at the company's premises, and several engineers from RR with different backgrounds such a system engineering, robust design, project manager, chief design engineer and technology specialist. The work was supported and reviewed throughout the project by the whole engine design team.

Implementation of activities of SDR0 for the helicopter engine

The following sub-sections summarise the application of Activities A–E and their associated tools (Figure 3) in the RR-LeanPD model for the helicopter engine.

Activities A and B: market study, benchmarking and data collection. Studies were conducted based on Activities A and B, to classify the project at the system level and to determine the corresponding levels of innovation. Some of the tools used in this stage were Classification

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Table 1. An example of a Value Spreadsheet used in activity C1.

Stakeholders	Value attributes		
Rolls-Royce	Cost	Cost A	Cost 1 Cost 2
		Cost B	
	Compliance		
	Manufacturability		
End customer	Efficiency	Turbine efficiency Compressor efficiency	
	Disruption		
	Serviceability		
Airframer	Weight		
	Mounting		
World and environment	Emissions		
	Safety		
	Regulations		

Table 2. An example of a Product Value Model for the helicopter engine.

	Airframer				Rolls-Royce			
Primary value attributes	Requirements related to power	SFC	Requirements related to weight	Weight	Requirements related to manufacturability	Manufacturability	Requirements related to cost reduction	Cost
Secondary value attributes		Electrical power		Lightweight materials		Design manufacturing		New materials
		Hydraulic power		Welded joints		Design assembly		Increase turnover
		Maximum payload				Design standards		Transportation
		Maximum range				TRL		
						Product optimisation		

Spreadsheet, Innovation Diagram and face-to-face interviews with experts and stakeholders. Establishing a preliminary understanding of customer needs and familiarisation with the product and project requirements result in more robust decision-making and faster progression of subsequent activities.

Activities C and D: exploration of customer value and strategy alignment. The following section provides a brief description of the work done for Activities C and D of the RR-LeanPD model (Figure 3). Understanding the customer value in the helicopter engine was conducted using the Value Spreadsheet which was populated after a series of meetings with engineers from the whole engine design team, and an example (with mock data) is shown in Table 1. The aim of this activity is to present the product value attributes for specific stakeholders in a logical way to enable a good understanding of their desires. For example, the end customers (e.g. military, airline companies) require an engine with high efficiency and low disruption, while enterprise itself (e.g. Rolls-Royce) is looking for attributes such as low manufacturability cost and short production times. To be better defined, few value attributes were broken down in greater detail, as shown for attribute cost in Table 1. Application of the Value Spreadsheets resulted in the generation of more than 100 value attributes (activity C1 in Figure 3) for different stakeholders which were extracted from documentation collected in Activities B1 and B3. A high number of attributes from many different stakeholders addresses one of the main principles of SBCE, which is the establishment of value focused PD process which enables a broader understanding of customers' needs and desires.

Identified value attributes were categorised and prioritised based on value attributes as shown in Table 1 (activity C2 in Figure 3) using the Product Value Model illustrated in Table 2. The most important value attributes are classified as primary or key value attributes. These constitute the foundation for the future activities. Key value attributes enable the focus to narrow to the real customer desires as suggested by SBCE principles.

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Table 3. Weighting the importance of key value attributes using AHP where 9 means absolutely more important attribute and 1/9 absolutely less important attribute.

	Cost	Manufacturability	SFC	Serviceability	Weight	Emissions	Safety	Regulations
Cost		3	1	7	9	9	7	7
Manufacturability	1/3		1/3	1/3	1/7	1/3	1/3	1/3
SFC	1	3		3	7	9	3	7
Serviceability	1/7	3	1/3		3	3	3	3
Weight	1/9	7	1/7	1/3		1	3	3
Emissions	1/9	3	1/9	1/3	1		1	1
Safety	1/7	3	1/3	1/3	1/3	1		7
Regulations	1/7	3	1/7	1/3	1/3	1	1/7	

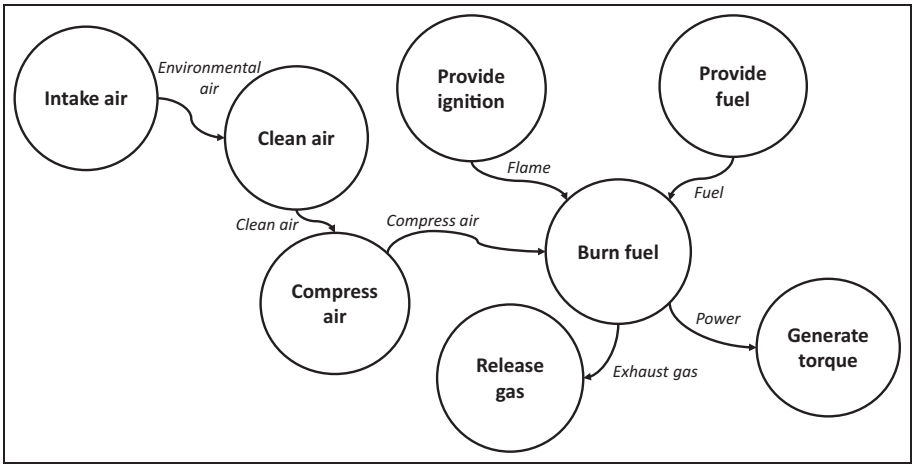

Figure 5. An example of simplified functional flow diagram for a helicopter engine.

Key value attributes were later translated into system targets using system target diagram (activity C3 in Figure 3) to provide measurable product requirements to enable the determination of what the product should deliver and what system changes will be needed.

The key value attributes were weighted against each other (activity C4 in Figure 3) using the Analytic Hierarchy Process (AHP) as shown in Table 3 in order to identify the most important value attributes. The first row and column are populated with value attributes. The upper part of the matrix (white) was populated over several interview sessions with engineers from the whole engine design team, while below the diagonal (grey) are the inversed values, needed to compute the weightings.

To calculate the importance of key value attributes (the weighting factor for each attribute), QUALICA software was used, and the results showed that four value attributes (Cost 35%, Specific Fuel Consumption (SFC) 27%, Serviceability 23% and Weight 15%) together scored more than 70%. Based on the results, engineers decided to focus on these four attributes alone and rule out others due to their lower importance. The matrix is designed to be filled in one row at the time, for example, weight is equally important as emissions and somewhat more important than safety and regulations. Similar case applies to all fields.

Activity E: development of system functionality. The aim of activity E from the RR-LeanPD model, shown in Figure 3, is to translate the four key value attributes into a set of engine functions. This was conducted in a session with the chief functional engineer in order to ensure the leanness of the PD process as it certifies that the engine functionality is directly associated with adding value to the customer and that unnecessary functions are eliminated.

The functional flow diagram (Figure 5) was used to analyse the engine functions. For example, to generate torque, the engine needs to burn fuel, which needs to be provided to it. There is no indicator of how this system should look only what it needs to do to generate torque. This is the main differentiator in the designers' mind, as he or she is not limited to physical design. This activity drastically increases the possibility of innovation and later to produce more alternative solutions.

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		FUNCTIONS							
		Intake air	Clean air	Compress air	Provide fuel	Provide ignition	Burn fuel	Generate torque	Release gas
KEY VALUE ATTRIBUTES	Cost			○	○		●		
	SFC	○	◎	◎	●	◎	●	◎	○
	Serviceability	○	●	●	○	○	●	○	◎
	Weight	◎		○		○	○		
○	Weak alignment		◎	Moderate alignment			●	Strong alignment	

Figure 6. An example of partial QFD to check the alignment of key value against functions.

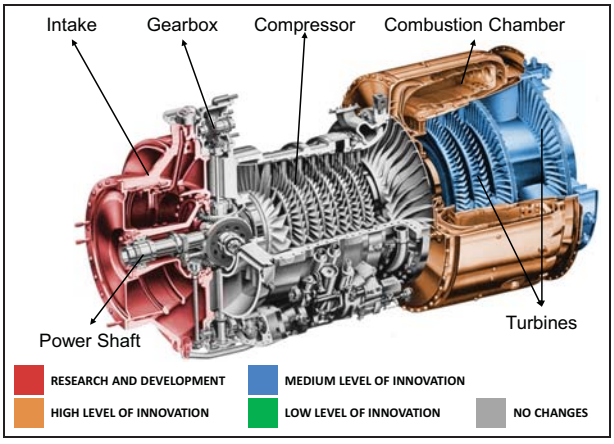

Figure 7. An innovation diagram for a helicopter engine.

The Partial Quality function deployment (QFD) matrix shown in Figure 6 was created to assess the alignment of functions with the key value attributes. This was done to ensure that functions really meet the customers' needs.

Product Concept Template (SDR0). The resulting data from Activities A–E were compiled in a document referred to as the Product Concept Template, to capture and present essential knowledge of the SDR0 phase in a single document with the purpose of enabling successful progression to the next design phase. The template focuses mainly on capturing the customer value and system functionality. It is designed in a way to encourage visualisation of results to reduce the length and complexity of the currently used reports and establish a standard document with the relevant knowledge created in the SDR0 phase.

Activities of SDR1 for the helicopter engine

The following sub-sections summarise the application of Activities F–H in the RR-LeanPD model, shown in Figure 4, for the helicopter engine.

Activity F: development of product architecture. The implementation of activity F starts where engine functions were identified from the functional flow diagram in activity E and shown in Figure 5, were broken down into sub-functions and then aligned with engine sub-systems and the key value attributes from the system level. The helicopter engine was divided into six sub-systems, as illustrated in Figure 7, according to the company's existing breakdown structure. Once they are identified, the functional requirements are associated with them.

For each sub-system, a level of innovation is identified using the innovation diagram as presented in Figure 7. This is a graphical tool by which an expected level of innovation is determined to each sub-system by interviewing experienced engineers involved in the project. The tool uses a colour code scale to enable time-efficient representation of the results. Sub-systems with higher levels of innovation are the ones that should generate more sets of alternative solutions in the coming stages, and the high-innovation sub-systems are likely to require more development resources.

Activity G: mapping the design space. The implementation of activity G defines the feasible area of potential solutions by setting design constraints and boundaries. This will help in narrowing down sets of solutions in subsequent PD stages.

Design constraints and boundaries were determined in four sub-activities by using several tools. For instance, documents from previous projects and competitors' products were consulted, and workshops with R&D engineers were organised. An example of a design constraint identified was the overall size of the engine, which was required to be fixed due to space limitations of the airframe.

Three out of the six engine sub-systems were selected for set-based development, as illustrated in Figure 7. Corresponding to the third stage of SBCE (develop concept sets in Figure 1), sets of alternative solutions were first extracted (activity G2 in Figure 4) using

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workshops and collection of the documentation of existing design concepts. Second, time for designers to ideate and think outside of the box was included (activity G3 in Figure 4), which resulted in several new design solutions presented. In addition, new solutions were developed by modifying existing designs or introducing new materials and technologies.

It is important to highlight that the purpose of this stage was not to reach a detailed design, as deliberate delay of decisions is a key factor of SBCE. The purpose was rather to explore innovative sets of alternative solutions that otherwise would have been ignored in conventional design approaches. By the end of activity G3 'Generate sub-system possible solutions', 25 alternative solutions were proposed at the sub-system level. Eleven solutions were proposed for sub-system 1, 6 for sub-system 2, and 8 for sub-system 3.The following subsection presents the convergence of these 25 sub-system solutions at a system level.

Activity H: filtering alternatives. Activity H corresponds to activity 4.1 'Determine set intersections' in Figure 1, and several tools have been implemented within this activity. The following is the presentation of functional means analysis and Pugh matrix. Functional means analysis was used to filter the set of alternative sub-system solutions to determine a set of solutions at the system level.

Table 4 shows an example of a functional means analysis where a number of alternative solutions are presented for the three corresponding engine sub-systems and their functions. Every number (e.g. 1.1, 1.2, …) represents a sub-system alternative solution for a specific function. These functions have been identified as result of activity E2 'Translate key value attributes into functions' and are illustrated in Figure 5. This means intake air function could be represented, in this case, in six different manners (1.1–1.6), while clean air function could be represented in five different manners (2.1–2.5). The same case is applied to the other two sub-systems. There are 2700 possible system combinations, which are the result of multiplying the sub-system alternative solutions for each function ((6 × 5) × (2 × 3 × 1) × (5 × 3) = 2700 as shown in Table 4). However, exploration of 2700 system solutions would be unfeasible; therefore, most of them were eliminated at an organised workshop with whole of the engine design team.

The elimination was conducted based on the following three filtering criteria: (1) impact of sub-system solution on key value attributes, shown in Figure 6; (2) engineers' knowledge and experiences; and (3) technology readiness level for each of the proposed sub-system solutions. That is how four alternative solutions were

Table 4. Filtering of alternative sub-system solutions with functional means analysis.

Sub-system	Functions	Part A: all proposed alternative sub-system solutions						Part B: Selected alternative sub-system solutions
		Alternative solution 1	Alternative solution 2	Alternative solution 3	Alternative solution 4	Alternative solution 5	Alternative solution 6	
Sub-system 1	Intake air (6)	1.1	1.2	1.3	1.4	1.5	1.6	1.4 1.6
	Clean air (5)	2.1	2.2	2.3	2.4	2.5		2.2 2.3
Sub-system 2	Provide fuel (2)	3.1	3.2					3.1
	Provide ignition (3)	4.1	4.2	4.3				4.2 4.3
	Burn fuel (1)	5.1						5.1
Sub-system 3	Generate torque (5)	6.1	6.2	6.3	6.4	6.5		6.4 6.5
	Release gas (3)	7.1	7.2	7.3				7.2

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selected for sub-system 1, being for the case of argument, 1.4, 1.6, 2.2 and 2.3, as shown in Table 4, Part B. For example, alternative solution 1.4 was selected because it best met cost attribute, and solution 1.6 was selected because it best met the serviceability attribute and at the same time they both had sufficient technology readiness level. Similarly, four alternative solutions for sub-system 2 (3.1, 4.2, 4.3 and 5.1) and three alternative solutions for sub-system 3 (6.4, 6.5 and 7.2) were selected using the data of the functional means analysis shown in Table 4. This resulted in identification of 16 ($(2 \times 2) \times (1 \times 2 \times 1) \times (2 \times 1) = 16$) possible system solutions formed from the combination of sub-system solutions as shown in Table 4, Part B.

As mentioned in section 'Activity G: mapping the design space', the whole engine has six sub-systems (shown in Figure 7), and in this case study, only three of them were used for set-based development. For this reason, only functions of the developed sub-systems are presented, but when using the term system solution, the authors refer to the configuration of all six sub-systems and their functions. Table 5 (Parts A to F) shows the intersection between sub-system alternative solutions to generate the set of system solutions. For purposes of simplification, Table 5 does not show unaddressed sub-systems. For the final convergence, an integration conflicts criterion was used together with the three criteria mentioned in the previous paragraph. Hence, the final set of six system solutions was formulated.

Part A in Table 5 shows that the first feasible system solution is configured from one alternative solution for each function of each sub-system (1.4, 2.3, 3.1, 4.2, 5.1, 6.5 and 7.2) in order to meet the cost value attribute target. A similar selection process applies for the rest of the tables where shaded cells indicate the selected alternative solutions.

A set of six feasible system solutions was formulated and then evaluated according to the impact on the key value attributes presented in Figure 6, using the Pugh matrix shown in Table 6 where each of the six feasible system solutions is rated on a scale from 1 (which corresponds to no impact) to 9 (which indicates that the key value attribute target is fully met).

Each attribute is assigned a weighting factor calculated in activity C4 'Validate and weight key value attributes' (described in section 'Activities C and D: exploration of customer value and strategy alignment'), and the total impact of a set of alternative system solutions is calculated by totalling the scores and multiplying them by the weighting factor. The scores were collectively agreed for each solution in a workshop with the whole engine design team. For example, the score for system configuration 1 which is formed to best meet the cost attribute is calculated as follows: $(9 \times 0.35) + (3 \times 0.27) + (1 \times 0.23) + (1 \times 0.15) = 4.34$.

Table 5. Formulation of the system configurations (system solutions).

Sub-system	Functions	Part A: System configuration 1 (to best meet cost attribute)		Part B: System configuration 2 (to best meet SFC attribute)		Part C: System configuration 4 (to best meet weight attribute)		Part D: System configuration 4 (to best meet weight attribute)		Part E: System configuration 5 (to best meet all attributes, version 1)		Part F: System configuration 6 (to best meet all attributes, version 2)	
Sub-system 1	Intake air	1.4	1.6	1.4	1.6	1.4	1.6	1.4	1.6	1.4	1.6	1.4	1.6
	Clean air	2.2	2.3	2.2	2.3	2.2	2.3	2.2	2.3	2.2	2.3	2.2	2.3
Sub-system 2	Provide fuel	3.1	/	3.1	/	3.1	/	3.1	/	3.1	/	3.1	/
	Provide ignition	4.2	4.3	4.2	4.3	4.2	4.3	4.2	4.3	4.2	4.3	4.2	4.3
	Burn fuel	5.1	/	5.1	/	5.1	/	5.1	/	5.1	/	5.1	/
Sub-system 3	Generate torque	6.4	6.5	6.4	6.5	6.4	6.5	6.4	6.5	6.4	6.5	6.4	6.5
	Release gas	7.2	/	7.2	/	7.2	/	7.2	/	7.2	/	7.2	/

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Table 6. Pugh matrix to evaluate the impact of alternative solutions on key value attributes.

Key value attributes	Weighting factor	System configuration 1 (to best meet cost attribute)	System configuration 2 (to best meet SFC attribute)	System configuration 3 (to best meet serviceability attribute)	System configuration 4 (to best meet weight attribute)	System configuration 5 (to best meet all attributes, version 1)	System configuration 6 (to best meet all attributes, version 2)
Cost	0.35	9	1	3	3	9	9
SFC	0.27	3	9	1	3	3	3
Serviceability	0.23	1	3	9	1	9	3
Weight	0.15	1	1	3	9	3	1
Score		4.34	3.62	3.84	3.44	6.48	4.8
Scale		1 – no impact		3 – moderate impact		9 – target fully met	

The solution with the highest score was recommended as the preferred solution.

Each of the possible system configurations is presented graphically in activity H5. Figure 8 is the example of simplified graphical representation of the recommended system solution, which is system configuration 5. This helps with the visual representation of the proposed solution that addresses the product requirements and key value attributes developed in SDR0. Other system solutions were presented in a similar way with the supportive data.

System Concept Template. System Concept Template (Figure 4) is a template to capture and present essential knowledge of the SDR1 phase in a single document with the purpose of enabling successful progression to the next design phase. The focus of this template is mainly on the set of alternative solutions, together with feasible regions of the design space. According to the set, recommendations for convergence are provided based on engineers' knowledge and results from the Pugh matrix (Table 6). In addition, this document also includes the level of innovation for each sub-system, design constraints, sub-system targets and risk analysis. Nevertheless, the System Concept Template follows the logic of the Product Concept Template (section 'Product Concept Template (SDR0)') of maintaining the minimal amount of information required to successfully pass the review gates. In addition, generated knowledge was captured and stored in appropriate format for utilisation in coming design stages or future projects.

Application of the RR-LeanPD model: benefits and challenges

The main benefit is the development of a structured PD model with well-defined activities and tools. This research-based case study helped to assess and test the RR-LeanPD model using a helicopter project. This demonstrated that the key opportunities of improvement such as enabling the innovation and clear information flow, and increasing the robustness of the requirements, have been addressed and evaluated. The learning in each design cycle has also been increased by ensuring that the right product knowledge is generated while performing each activity and captured in a single document called 'Product Concept Template' in SDR0 and 'System Concept Template' in SDR1. This has reduced the time engineers currently spend on lengthy reports and presentations. The demonstration of reduced project risk was outlined by increasing the confidence in the selection of concepts through the consideration and exploration of sets of alternative solutions. Several future challenges have also been

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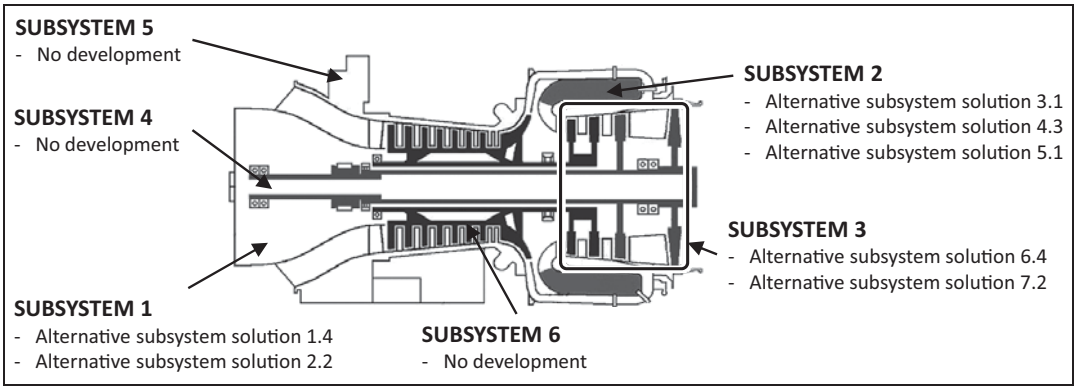

Figure 8. Simplified graphical representing of recommended system configuration 5.

identified such as establishing a common terminology across the business units and to further establish the knowledge-based environment to enable dynamic capturing, representation, retrieval and reuse of relevant knowledge throughout the PD in lean environment. Furthermore, the need to address the supply chain collaboration has also been identified.

Conclusion

This article presented a research-based case study where the principles of SBCE were embedded in an existing PD model. The resulting lean model has been applied on a helicopter engine to evaluate its value and its role in the lean transformation journey for the SDR gates SDR0 and SDR1. The existing SD&I model has been improved by transforming it into the RR-LeanPD model which is based on SBCE. This improvement has been achieved by the development of a structured PD model with well-defined activities, tangible outputs and tools. The tools were associated directly to each activity in order to provide clear guides regarding which tool to use and what has to be done. Such activities focused on core enablers in lean PD, such as value focus, set-based solutions, integrated documentation, knowledge creation and innovation. Feedback from engineers highlighted the good possibilities for improvement in the PD process in terms of available alternative solutions, level of innovation and decreased risk of rework. Future work will further develop the RR-LeanPD model to unleash early design stage improvement possibilities and extend the model to cover the product life cycle with the incorporation of sub-system and component levels.

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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