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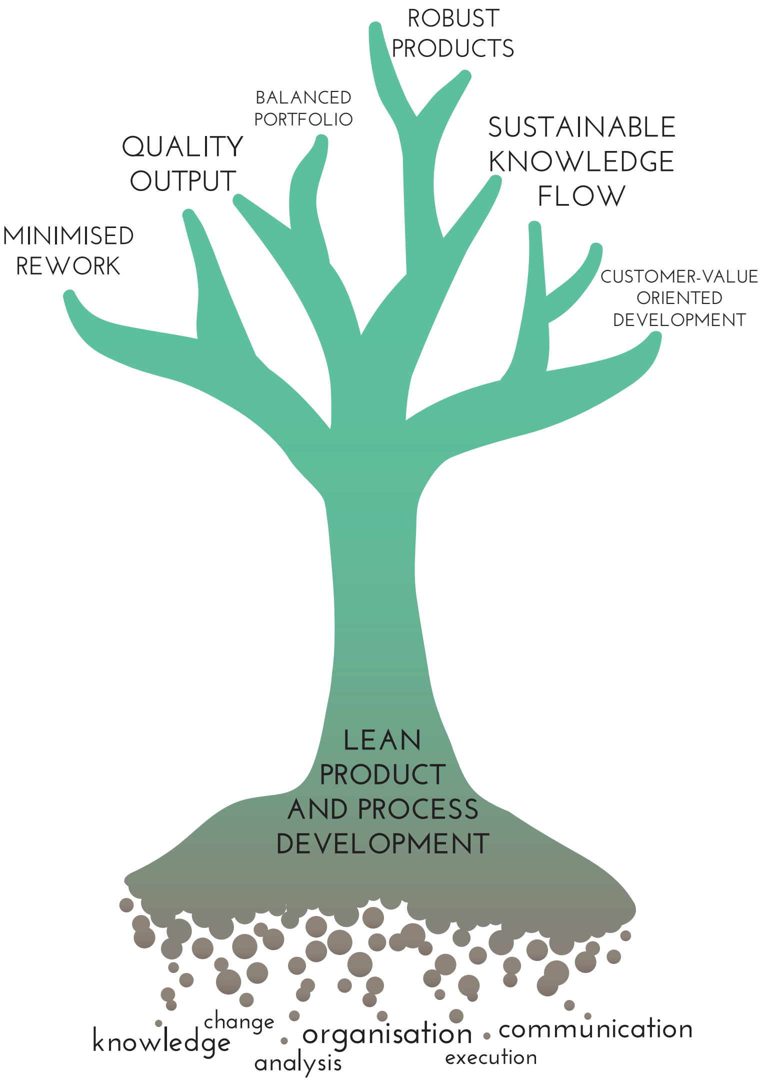

Mitigating design error root-causes in product development

Integrating “lean thinking” into design process error-proofing in Philips product development

Master of Science in Engineering Thesis

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Abstract

Conventional product development is challenged with quickly changing globalised markets which demand faster market introductions and effective innovation processes. With current practices known as point-based concurrent engineering, tight schedules and budgets tend to result in poor product quality and design errors which in turn lead to rework and budget overruns. These problems also occurred at Philips BG Coffee which initiated the research for mapping the root-causes of design errors and finding applicable countermeasures for advancing the currently established development process.

The design process root-cause analysis – built upon a design task execution model – identified improvement areas for BG Coffee in the fields of "organisation", "communication", "analysis" and "knowledge" regarding lack of standard practices and poor knowledge flow. These go in line with the observations of other research findings in various industries and has led the trend of implementing lean tools as validated effective countermeasures.

Lean product and process development framework focuses on creating a sustainable knowledge value stream which emphasises learning cycles to produce optimised and proven product systems. The principles and tools build an aligned approach for "decisions based on facts" mentality and strives for gathering real data to address system interactions and performance trade-offs. The core lies in the set-based concurrent engineering development model which was also determined as the desired state for the BG Coffee development process.

The proposed implementation plan for mitigating identified root-cause errors in BG Coffee involves a step-by-step process of establishing "lean enablers" and advancements of the current organisational practices. It provides the transition guidance from point-based to set-based concurrent engineering.

Keywords: design process error-proofing, lean product and process development, set-based concurrent engineering, knowledge management

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I would like to thank the BG Coffee development department for initiating the project and providing insights and data of their innovation processes to conduct action research. I appreciate the cooperation of engineers and leaders who contributed their time in carrying out the study. My special thanks go to Suzanne van Egmond for support and guidance as a true lean leader. Also, Wim Wielens for providing feedback on organisational fit of the proposed new approaches for the technical team and encouraging the change environment for future work.

Lastly, I would like to thank my academic supervisor Göran Gustafsson for arranging the collaboration and supporting the research with his knowledge and reflections through-out the process.

Kerli Kustola, Gothenburg, June 2018

Contents

List of Abbreviations

DERC – design error root-causes
DPEP – design process error-proofing
DSM – design structure matrix
FMEA – failure modes and effects analysis
I2M – idea-to-market
ICD – innovation classification diagram
IPD – integrated product development
ISF – information structure framework
LAMDA – look-ask-model-discuss-act
LCM – life-cycle management
LPPD – lean product and process development
PBCE – point-based concurrent engineering
PDCA – plan-do-check-act
PDM – product development mechanics
QFD – quality function deployment
RAMS – reliability, availability, maintainability and supportability
RCA – root-cause analysis
RPN – risk priority number
SBCE – set-based concurrent engineering
TOC – trade-off curve
TRIZ – theory of inventive problem solving
VOC – voice of the customer
VSM – value steam mapping

1

Introduction

Development departments are continuously trying to improve their process in order to launch quality products within time and budget. With highly competitive global markets and quickly evolving customer demands, the development of new products is under increased pressure to minimise time-to-market (Khan et al., 2013). This has led the product development research to finding best practices and developing new design process error-proofing (DPEP) methods which would advance the development process (Khan et al., 2013; Chao et al., 2001).

Chao (2005) has defined design errors as:

> *"actions and decisions in product development which result in a failure to meet the planned or intended outcome."*

Design errors may occur as product defects or internal development issues as redesign loops. So far, these have been largely accepted as part of the development process nature as the conventional point-based engineering model is an iterative process (Ward and Sobek, 2014). However, the design decisions made along the process determine the success rate of a product as these account for the greatest effect on product cost, feature and time-to-market. The occurrence of design errors result in product launch delays, budget overruns, loss of quality and increased maintenance work (Chao and Ishii, 2004). This in turn can lead to loss of market share and loyal customers which result in decreased profits. For example, studies have shown that over half of the quality loss can be attributed to errors made in the design process (Chao, 2005). In addition, these create rework which is considered as one of the main wastes – activities which do not create value to the customer, and therefore need to be eliminated to achieve leanness – in the product development process (Morgan and Liker, 2006). Thus, the prevention and detection of design errors should be the basis for development process improvements to create a more robust system.

Design process errors are considered latent – they cause detrimental consequences while surfacing after a long period of time, (Chao, 2005) – which makes them harder to track. In addition, the errors can rarely be mapped to only one root-cause as these usually result from the interaction of multiple factors. However, DPEP tries to challenge it with design strategies and tools/methods to predict as well as prevent potential errors which might occur during the development process (Chao et al., 2001). It serves the intent of minimising rework and increasing design process quality by mitigating the identified design error root-causes in the organisation.

The approach aligns with emerging lean product and process development (LPPD) methodology which focuses on value creation and the elimination of waste (Khan et al., 2013). The LPPD approach has been formed through studies of the Toyota Development System which accounts for continuously outperforming their competitors in the automotive industry (Sobek et al., 1998). The identified principles of LPPD are now being put into practice in other organisational environments in order to validate their positive impact and find current best practices for product development management (Khan et al., 2013).

Design process error-proofing and "lean thinking" serve the aim of effectivising the development process in order to produce high quality and customer-oriented products with reduced time-to-market and cost.

1.1 Background

Philips BG Coffee product development department in Drachten, Netherlands, presented a problem in the visibility of small design errors which occur in product development projects and lead to defective products. The department handles the idea-to-market (I2M) product development phase of consumer products which are mass produced. The problem formulation was based on an integrated product development (IPD) project of a key component in a coffee machine which resulted in an extensive follow-up project.

1.1.1 Problem Statement

The follow-up project took extended time and high additional cost to mitigate the design errors made in the process. The errors involved small changes to a system module which led to unexpected system behaviour and the appliance not meeting its target performance specifications. The issue surfaced after product launch in early production randomised testing of the appliances. It resulted in triple quality control of all the shipments and simultaneous root-cause analysis of the defect for system improvements. The follow-up project uncovered additional problems to mitigate and the initial issue was resolved by changing that part of the system back to its previous design.

The root-cause analysis (RCA) of the project surfaced areas of improvement for the product development process currently in use. These involved visibility of knowledge gaps, awareness of system (functional) interrelations, available knowledge reuse, design communication principles and handling of “non-critical” design features. These observations identified an opportunity for a problem-solving project in order to improve Philips BG Coffee development process which initiated this Master Thesis project.

1.2 Purpose

The purpose of the project is to improve the product development process in Philips BG Coffee department in order to avoid design errors which create rework, increased cost, delays in the projects and other related issues. Thus, the aim is to present an implementation plan of countermeasures with part of the solutions further validated with the user group. The countermeasures are developed to mitigate the identified root-causes of design errors in the specific organisational process environment – small project teams with limited resources and budget constraints developing medium complexity consumer products. This should result in minimisation of project cost overruns, launch delays and quality loss. In addition, it strives for organisational excellence in managing product development projects with small teams.

1.3 Research Questions

From the given problem formulation and the purpose of this research, two fundamental questions were identified to scope the work. Both are in relation to the organisational environment in Philips to serve the principles of action research (Bryman and Bell, 2011). First, the current situation in the Philips development department is analysed with the focus on identifying and understanding the root-causes of design errors.

RQ1. Why do design errors occur in the current Philips BG Coffee development department’s way of working?

Next, according to the findings, suitable countermeasures are developed based on state-of-the-art development process improvement practices for error-proofing the design process. As Philips strives to be a lean organisation, the innovation should be led by applicable principles.

RQ2. Which design process error-proofing methods and lean practices form a suitable base for improving the Philips BG Coffee development process?

1.4 Outline

The thesis begins with the presentation of the research strategy and description of the applied methodology. This is followed by the analysis of the organisational and current product development process environment in the BF Coffee development department. It leads to identifying the root-causes of design errors and possible improvement areas which will be the basis for a literature study.

Next, the available research findings and best practices in Philips are used for countermeasures development and evaluated for organisational fit as well as impact. Those best suited are further refined for an implementation plan and part of them tested in the applicable user group.

The results are presented as future work suggestions with the developed plan to improve Philips' current process. The thesis ends with a discussion on design process error-proofing and applying lean methodologies in the given environment, followed by concluding remarks.

1.5 Delimitations

The long-term effect and results of the implementation plan in the organisational environment are not covered in the thesis due to the time constraint. The data reviewed was limited to 12 closed IPD projects conducted in the BG Coffee development department which were found eligible with the available documentation.

2

Methodology

The thesis was carried out based on an action research strategy which is designed for a practical problem-solving approach. It is defined as experiments on real situations within an organisation and are intended to assist the institution in their outcome in order to overcome the identified deficiencies. It is a symbiosis of academic theory and practical action resulting in a solution or an improvement of the given problem/contextual issue (Bryman and Bell, 2011).

This chapter further describes the research design and applied methods. As defined in Bryman and Bell (2011), action research does not have a specific structure, it can be carried out as organisationally fit given the problem statement. The usual stages involve an iterative process of problem identification, planning, action and evaluation, similar to a Plan-Do-Check-Act (PDCA) cycle.

2.1 Research Design

Given the action research process stages, it was proposed by the Philips supervisor to use a lean methodology tool called the A3 problem-solving approach as an aid to guide the activity flow of problem-solving for process improvements.

The method name comes from the standard template size – an A3 paper – and facilitates clear communication and following a standardised process. It is a well-known tool in the LPPD methodology in a variety of applications – proposing a plan, communicating the current status, sharing information or guiding problem-solving (Morgan and Liker, 2006; Ward and Sobek, 2014). The latter template was used for the given research and involves seven different and interrelated stages, as shown in fig. 2.1 and described in Shook (2009), which relate to the action research process. It corresponds to the lean development cycle LAMDA – look-ask-model-discuss-act – which is an advancement from PDCA (Ward and Sobek, 2014). It encourages the practice of first-hand observations and facilitates deep investigation in the heart of the problem as well as further discussion to find the best possible solutions.

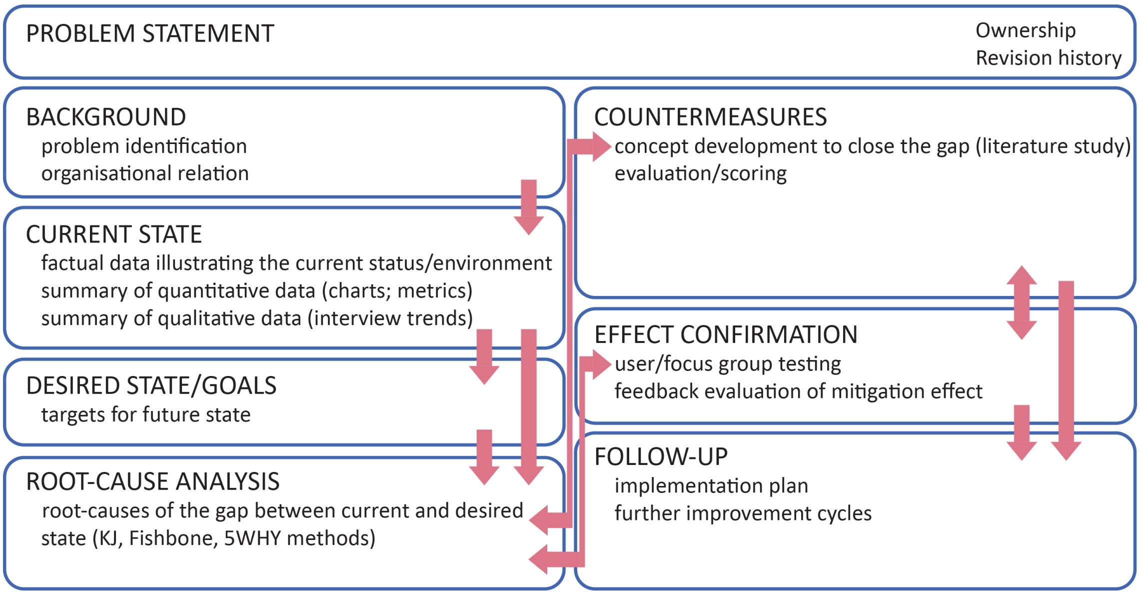

Figure 2.1: A3 problem-solving template

First, the improvement action is given as a heading of the A3 document. This communicates the essence of the organisational issue which is being addressed. Next, the background description creates the understanding of the organisational relation to the problem. Following with the information of factual data about the current state which is gathered and/or analysed regarding the process involved to describe the situation at hand. Given the problem formulation and current state, the desired state is crafted and represented as goals/targets to achieve with measurable indicators. Further, the root-cause analysis determines the reason for the gap between the current and desired state, indicating the underlining problems which need to be addressed in order to improve the process effectively and create a sustainable system (Shook, 2009). These parts correspond to the problem identification of the action research and answer the first research question stated in section 1.3.

Next, follows the modeling and planning phase. It starts with the development of countermeasures based on research literature and organisational knowledge. The concepts are evaluated and suitable solutions presented with an implementation plan. This leads to the action stage which is carried out in the practical environment. It involves testing the developed countermeasures in the process. Last, the effects of the proposed solution are analysed and evaluated to assess whether the identified gap was closed to reach the desired state. The outcome will be the basis for the following improvement actions (Shook, 2009). In the given time-frame the evaluation was done on a test project and a refined implementation plan presented for future work answering to the second research question stated in section 1.3.

2.2 Applied Methods

The presented research strategy stages are supported by applicable research methods and problem-solving techniques. These involve data gathering, root-cause analysis, concept development and validation methodology which are described in the following sections.

2.2.1 Data Gathering

In order to validate the problem and define current organisational environment, qualitative and quantitative data was gathered regarding the development process. Qualitative methods encompassed in-depth interviews and observations. Both were carried out in the "working environment" as the researcher was placed in the department during the study. Observations involved day-to-day office work experience through-out the four-month period. The interviews were prepared as semi-structured with guiding questions on different topics on the development process and formally documented (Robson, 2011). These were conducted in two phases – to define the current state of the process and additional information for root-cause analysis. The outline can be found in Appendix B. In total, there were 14 individuals interviewed, listed in table 2.1, varying in duration of 45 minutes to 1.5 hours.

Table 2.1: Interviewees

Position	**Experience** (yr)	**Current Department** (yr)
Mechanical engineer	20+	4 (months)
Quality project lead	10+	9
Quality project lead	10+	4.5
Mechanical lead engineer	20+	5
Function developer	2	1+
Project/program manager	20+	4
Function developer	3	1
Senior LCM engineer	25+	15+
Mechanical lead engineer	25+	10+
Module engineer	25+	7
Quality project lead	15+	8
Field quality engineer	5+	5
Mechanical lead engineer	25+	1
Mechanical group lead engineer	10	10

Quantitative methods involved studying closed IPD projects through the department's database which included development process deliverables and post launch data, such as milestone reports and failure call-rate sheets. These were the basis for factual data of the projects' performance status.

Later in the research process, for validating the effect of proposed countermeasures additional interviews were held with the product development mechanics (PDM) group.

2.2.2 Root-Cause Analysis

The basis for further analysis was built by first identifying the root-causes of design errors from gathered data. Chao (2005) has developed a categorisation of design errors based on the development task model shown in fig. 2.2. The classification system concentrates on design process errors which are at the start of the cause-effect chain determining the product quality. It categorises root-causes in order to guide error-proofing and mitigation of underlying organisational problems. As such, the given model was found most suitable for addressing product development process improvement areas in the given thesis.

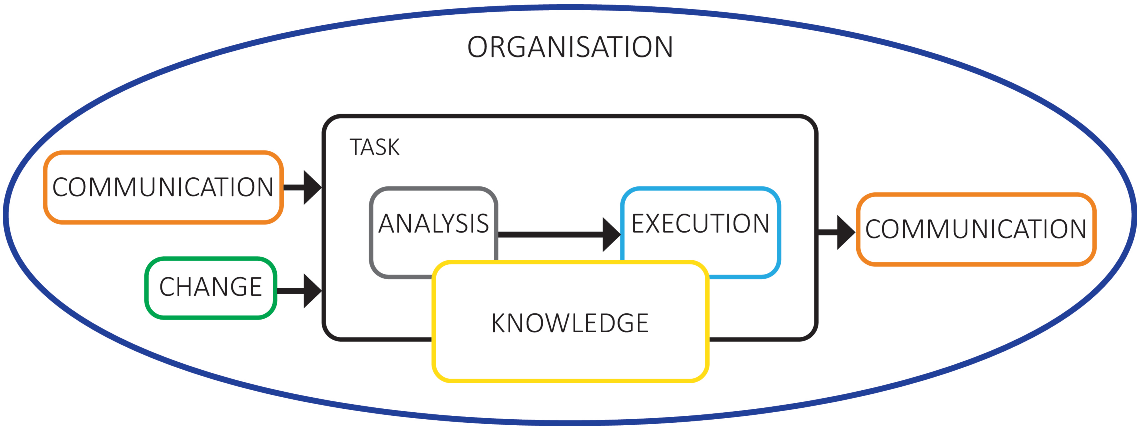

Figure 2.2: Influential factors in a design task (Chao and Ishii, 2004)

It involves six factors – knowledge, communication, analysis, execution, change and organisation – which affect the processing of a design task.

- Knowledge – inadequate use of existing knowledge, decisions made without the needed knowledge and incomplete understanding of the system itself
- Execution – human errors and not following the given guidelines
- Change – noise as in decisions made by other actors which alter the design task

- Analysis – failures where external and internal factors are underestimated or neglected, such as system interactions and behaviour of sub-components
- Communication – errors in information delivery as an input to the design task – requirements, instructions and guidelines – as well as inadequate reporting of the task completion
- Organisation – contextual environment involving ways of working, like standard processes put in place, and leadership of development projects

These define the general categories for design error root-causes (DERC), further described in fig. 2.3, in the development process.

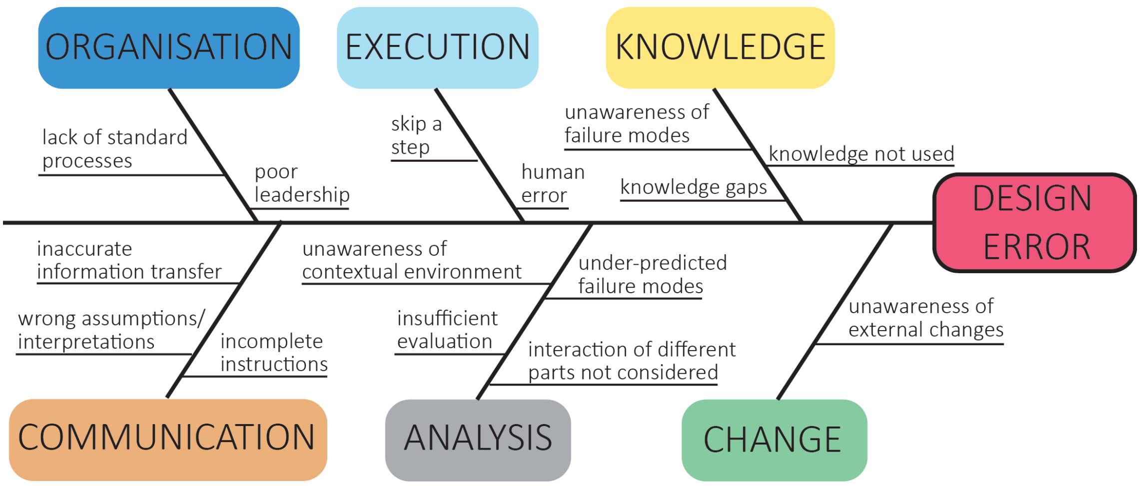

Figure 2.3: Design error root-cause classification model adapted from Chao (2005)

The design errors found in development and post-project data were classified given the information available. The "organisation" branch was neglected in this process as it was difficult to track down the organisational influences in the occurrence of the error. The other categories were more tangible for identification, such as incomplete analysis, inaccurate instructions or unawareness of part characteristics' behaviour.

In order to link the DERC to the development process deficiencies, qualitative data was analysed. First, the identified problems were clustered using the affinity diagram (i.e. KJ method) (Ullman, 2010). Further, main shortcomings were linked to the development project Fishbone's major categories and decomposed to several root-causes with the help of the 5WHY structure (Shook, 2009). These were additionally associated to the design error classification (including "organisation") – which process deficiency root-cause contributes to what design error root-cause. As the qualitative data allowed for further investigation and determining the contextual environment of possible error occurrence, the organisational inefficiencies could be addressed in the root-error identification this time. The relations were represented in a tree diagram. The RCA process flow is depicted in fig. 2.4.

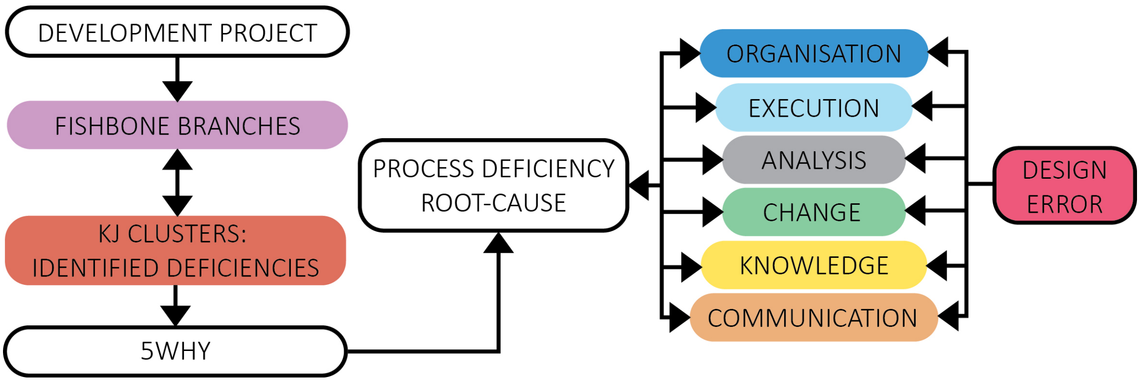

Figure 2.4: Root-cause analysis flow

For analysing the effect of the process root-causes, the Pareto chart was used to determine the "vital few" of DERC areas which should be the focused for mitigation. This led to defining the improvement directions for countermeasures' development.

Through-out the process colour-coding is used to better follow the analysis and linkage between models. The legend for it is shown in fig. 2.5.

Figure 2.5: Legend for colour-coding

2.2.3 Concept Development and Evaluation

Given the RCA outcome, a literature study and examination of the best practices in Philips were used for countermeasure development. The basis for process improvement directions were the combination of identified areas and maturity of the current toolbox development in the department, initiated by the PDM group leads.

The literature study was carried out through the use of keyword search in various databases, tracking references and previously known sources or suggestions from supervisors. The focus was on state-of-the-art DPEP and lean initiatives in product development which led to recent theory developments and case studies. The practical implementations and reviews of best practices in the industry were most fruitful for concept development. The applicable keyword-set included: "design process error-proofing", "lean product development techniques", "poka-yoke in design development", "design communication" etc. The Chalmers Library, ProQuest and other scholarly search engines were used to find and retrieve relevant literature.

The countermeasures were crafted on the current development process structure and available toolbox base. A new process flow was the starting point for evaluating implementation of suitable tools and revision of established processes. The identified methods were analysed on the dimensions of error-proofing (Chao, 2005), shown in fig. 2.6. “Error factors” correspond to the described design error root-cause nature. In this study, the basis for it were the improvement areas addressed by the tool to determine the possible scale of error mitigation in the given organisational environment. “Solution levels” refer to the scope of the problem that is attempted to be fixed, either a specific problem, process or entire system as shown in table 2.2. Finally, the “robustness level” indicates the performance of the error-proof mitigation for future errors – if it aids, guides, inspects, detects or prevents them, described in table 2.3.

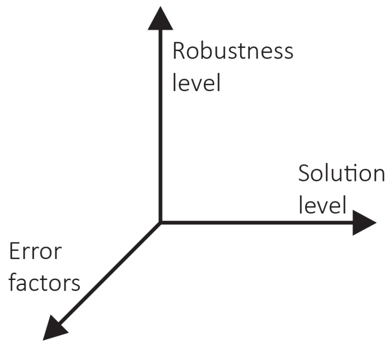

Figure 2.6: Dimensions of error-proofing (Chao, 2005)

Table 2.2: Solution levels (Chao, 2005)

Level	Scope	Description
0	Denial	Rationalise without fixing the problem, “one-of-a-kind”
1	Problem	Fix the specific problem each time, reactive
2	Process	Improve the process individually
3	System	Improve the entire system or organisation, proactive

Table 2.3: Robustness levels (Chao, 2005)

Level	Method	Description
1	Tool	General aid for analysis and design
2	Improvement	Simplification or guidance to the process
3	Inspection	Design review or final inspection of system
4	Detection	Detect the error immediately after being made
5	Prevention	Eliminate the possibility of performing an erring action

Given the outcome of the evaluation, an implementation plan for reaching the proposed process flow state was presented as a step-by-step plan. Further evaluation of organisational fit for the roll-out plan was conducted through informal discussions. The principles were tested on a user group of three engineers, presented in table 2.4, conducting a platform development project. The tested methods were chosen given the current time-frame fit and project status.

Table 2.4: User group representatives

Position	**Experience** (yr)	**Current Department** (yr)
Senior system architect	15+	15+
Module engineer	20+	10+
Senior function developer	N/A	N/A

2.3 Research Quality

As this research design corresponds to qualitative action research, the quality aspects reliability and validity are translated to the assessment of trustworthiness and authenticity (Bryman and Bell, 2011).

According to Bryman and Bell (2011) trustworthiness involves four criteria: credibility, transferability, dependability and confirmability. In order to validate credibility, the data was acquired in triangulation to verify the result based on multiple sources. Also, the in-depth interview analysis and outcome were discussed with the respondents to ensure its truthfulness.

As qualitative research is heavily dependent on the current situation, it makes it harder to generalise the results. As such, it needs to involve detailed descriptions of the situation to be transferable to other cases as learnings (Bryman and Bell, 2011).

With action research, additional conflicts of interest may arise, like financial gain and biased viewpoints (Bryman and Bell, 2011). Through-out the research, it was important to further improve the understanding and create valuable feedback for the organisation in order to advance their current situation with aligned vision and improvements from an objective point of view. Thus, the thesis is written more for discussion with the involvement of many organisational parties – engaging different representations of viewpoints – and connected to general academic literature findings for bias avoidance.

3

Current and Desired Process State

This chapter presents the results of determining the current state of Philips development process of IPD projects in the given department. It covers the first phase of the A3 – examining the origin of the problem and collecting relevant status information (Shook, 2009). As stated in section 2.2.1, the data was gathered through project deliverables and interviews with department employees who are listed in table 2.1.

3.1 Process Description

The development projects follow a Stage-Gate® approach to standardise project execution (Ullman, 2010). The process involves eight phases, described in fig. 3.1 with dark red lined gates, which all encompass a set of deliverables that are reviewed in the milestone consolidation event (gate). Based on the stakeholder meeting, the decision of project continuation is made: pass on to next stage, pass on with a conditional go or stop it.

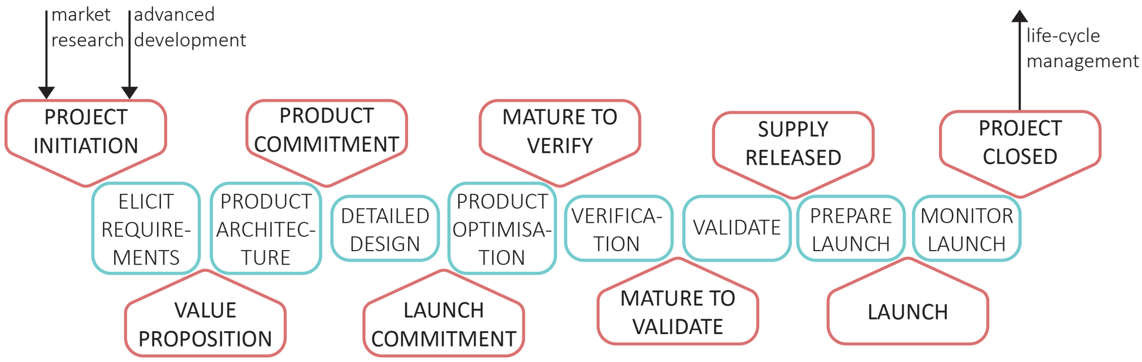

Figure 3.1: Philips development process Stage-Gate® model

This sets the current design process maturity at the "disciplined" level, as described by Chao (2005), as a formalised phase review is implemented in the process. The Stage-Gate® structure is supported by a system decomposition model which links the initial "voice of the customer" conversion to product requirements and verification, commonly known as the "V-model" in software development – an extension of a waterfall structure (Ullman, 2010).

The project is initiated based on market research and advanced technology development industrialisation opportunities. These serve the importance of time-to-market principles by incorporating recent technological advancements to better meet evolving customer needs (Ullman, 2010). After the product launch, the project is transferred over to the life-cycle management (LCM) team.

The development project process data was compiled in a Fishbone diagram, shown in fig. 3.2. It entails the organisational, measurable, process, material, people and tool factors which support and guide the execution. These were discussed during the interviews in order to map the elements and review their current state from different engineering groups' perspectives.

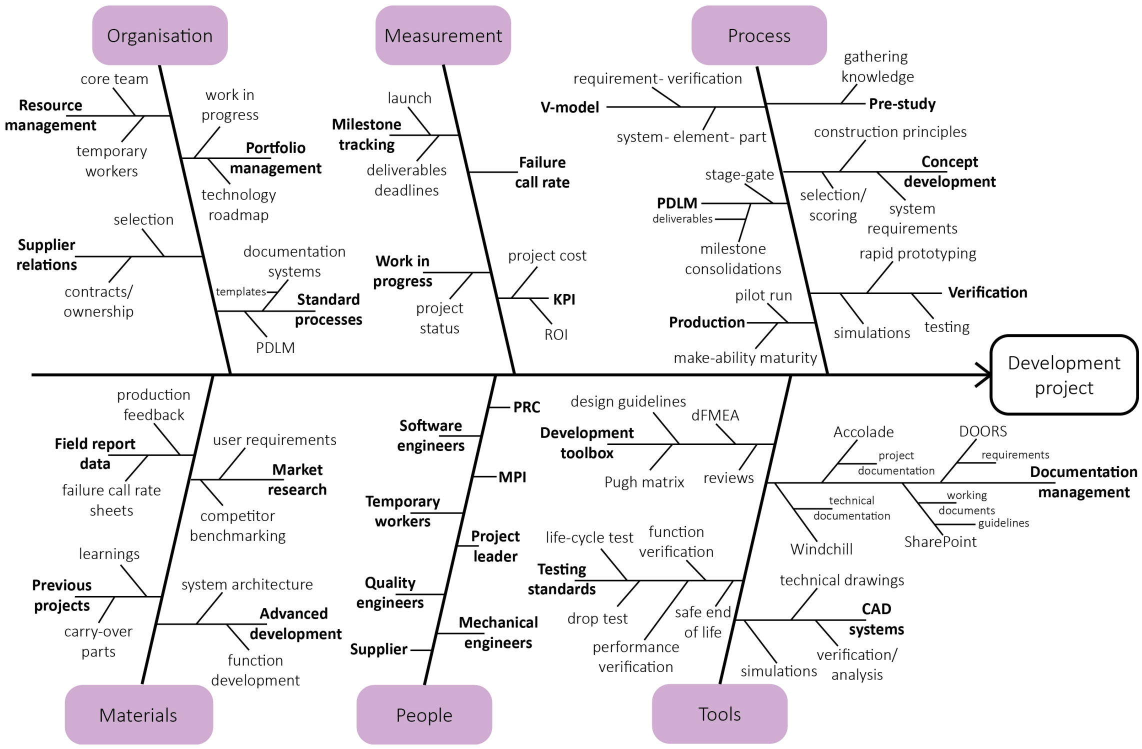

Figure 3.2: Development project Fishbone diagram

The interviewees involved mechanical and quality engineers, function developers and project leaders, presented in further detail in table 2.1. The overall experience is relatively high in the department with most employees exceeding ten years of practice in their field and found their way to the current department through job rotations within Philips. Discussions on the supportive factors led to understanding of the positive and negative effects of the current ways of working. The main reoccurring statements are shown in fig. 3.3.

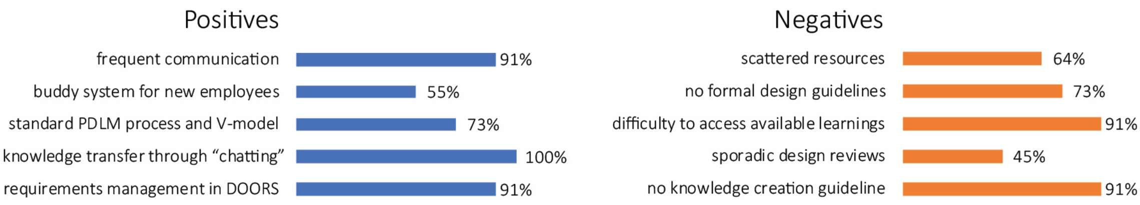

Figure 3.3: Development process current ways of working

The favourable practices involved using a standardised project execution process – recently modified to align every Philips development department process –, short and frequent communication lines and certain effective documentation management systems. The open office layout is used to facilitate quick discussions between functional and project team members. For example, knowledge is usually also transferred through "informal chatting" as one of the engineers described it as:

> *"...if I run into unexpected issues then I ask around on the (department) floor who has experienced something similar to assist possible mitigation ways."*

Failure Modes and Effects Analysis (FMEA) was the most used and effective method available in the current toolbox as it guided the technical development process. Also, the Pugh matrix was known for concept evaluation and some group leads employed PDCA for action tracking. Furthermore, the requirements flow-down software was appreciated and recently there had been a transition to new technical and project documentation systems which were expected to advance structure and communication principles.

The main deficiencies were related to lack of standardised tools for design communication and evaluation, incomplete documentation/missing knowledge management and scattered resources. Tools and methods used in the design development were not formally established across all project teams. Available ones were sometimes not used to their full extent or developed maturely. This was validated by recently on-boarded employees who were not fully aware of common practices. The balance between structured methods and freedom for individual ways of working was strongly leveraging towards the latter, as stated by one of the lead engineers:

> *"...so far engineers were not given a toolbox (which we are now developing) for guiding design tasks, everybody were let to find their own way of working."*

In addition, many standard procedures – like design reviews – were held less frequently and the involvement of temporary workers created some task translation issues. Furthermore, the documentation principles varied as traceability suffered from every team setting up personalised documentation flows in the project folder in SharePoint. As such, most learnings and knowledge did not reach farther from the project team's shared folder and was not easily accessible to others, as one of the statements was:

> *"...if you are interested in some of the testing data or root-cause analysis on a closed project issue then finding anything in the previous folders is troublesome as you do not know how to navigate."*

Many of these practices were due to "busy schedules" as the amount of work in progress was high and engineers needed to divide their time between multiple projects. Many employees found it inefficient to manage and shift between different developments as they experienced loss of focus and productivity. Numerous statements involved:

> *"...with a lot of time pressure and varying projects, the details start to slip and less time is left to deep-dive into individual development tasks."*

Also, the project initiation of an IPD project was sometimes unclear. There is a distinction between research and development functions as separate working groups with the former validating function feasibility and the latter incorporating these in consumer products. However, the translation of projects between parties was blurred when the industrialisation phase of a few developments were rushed with great risk and uncertainties due to market needs. This led to disproportion in workload between the departments and caused additional rework for the development side, if the maturity of concepts was found insufficient for industrialisation.

In addition, some of the projects were modified and executed off-track which led to continuous "fire-fighting" to manage product launch on time. As such, the aligned principles and project management methodologies were not applied across all projects. Moreover, the knowledge and experience in the department was incompletely spread due to poor knowledge management practices which led to reoccurring design errors.

The organisation was acknowledging the problem as the interviews showcased engineers' concerns and ideas to advance the current situation. Also, the PDM group had initiated an improvement action to standardise the way of working by developing a toolbox for the engineering group which would consist of templates and guidelines for standardising the design task execution. It was still in a "draft" form after two years as project work was prioritised and lack of attention was given for organisational advancements.

3.2 Project Performance

To observe the current performance of project execution, 12 closed IPD projects were reviewed through milestone reports, design and quality testing documentation and failure call-rate sheets. The projects ran between 2011 and 2018 and varied in scope from incremental changes to new platform development. The information gathered included milestone tracking, commitment to R&D budget and launch deadline, project retrospect, documentation and found design error occurrences during development and after launch. Each phase was studied and compiled in data sheets to get an average overview of the performance metrics for the company.

The milestone initial deadlines were compared with actual meeting dates and considered "missed" when delayed more than two weeks as it is the standard in the organisation. R&D final investments and launch dates were compared to the "handshake" project confirmation meeting commitments. The mid-milestones and estimated/actual budget comparisons showcased project execution variations and unexpected outcomes – increased investment needs and rework in late project phases which delayed milestone consolidations.

Further, the documentation was evaluated based on reporting of deliverables in the database and relevancy of the content. Especially documenting learnings varied across projects as retrospect principles were not very strongly implemented in the department. Also, some of the delivered documents rather encouraged a "tick" than the creation of value which resulted in a decrease of covered documentation percentage.

Lastly, the design errors were gathered through issue reports and failure data. During the development, these were presented in an issue list in milestone reports and RCA led to understanding of possible reasons for errors' occurrence which was later used for DERC data analysis. In addition, failure call-rate data sheets gave a good overview of design errors found after launch, which led to field defects, and further information on implementations which were scheduled for mitigation.

The metrics on project performance gave an understanding of how the process deficiencies affect the projects outcome and created basis for tracking improvements.

3.3 Desired State

Based on the current project performance, the desired state was determined with new targets on the given metrics. These served the purpose of project delay/rework avoidance due to design errors as the issue statement in the A3. By identifying the root-causes of current development process deficiencies and implementing proper countermeasures, the new state should archive the goals presented in table 3.1.

Table 3.1: Desired state targets

Metric	**Target**
Milestone deadlines missed	reduce by 50%
R&D budget overrun	reduce by 50%
Learnings covered	100%
Deliverables documentation covered	100%
Design errors during development	reduce by 50%
Design errors post launch	reduce by 100%

4

Analysis

This chapter describes the A3 analysis part of the root-causes which create the gap between the current and desired state. The findings are translated to improvement areas to guide the following countermeasure development. The analysis is easier to follow with the understanding of the used colour-coding explained in fig. 2.5.

4.1 Root-Cause Analysis

As described in section 2.2.2, the design error root-cause classification model was used through-out the analysis in order to identify the problematic areas in the Philips BG Coffee product development system. First, the gathered project design error data was reviewed and classified under an applicable root-cause based on found reports. The “organisation” DERC was neglected for this analysis phase as it was hard to trace without explicit knowledge of the organisational influence at the error occurrence as it affects all the categories considering the design task model in fig. 2.2.

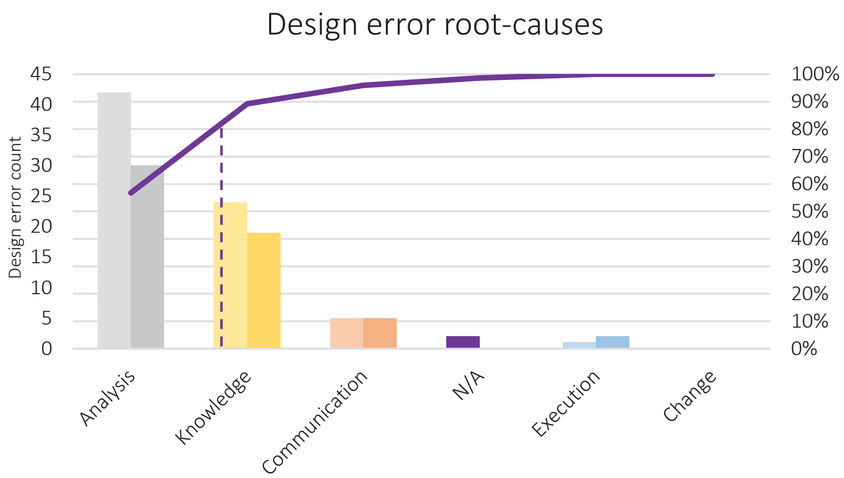

Figure 4.1: DERC analysis results for development phase (left column) and post launch (right column) *(colour-coded)*

The result of the classification for found design errors during development and post launch are seen in fig. 4.1. The DERC "analysis" and "knowledge" were the high scorers and identified as the "vital few" according to the Pareto principle. The examples for the two categories are covered in table 4.1.

Table 4.1: Occurred design error examples in "vital few"

Analysis	**Knowledge**
Unawareness of sub-system interaction (e.g. part placement influence)	Incomplete understanding of material properties (e.g. material degradation)
Underestimated carry-over parts behaviour risk	Unidentified knowledge gaps (e.g. supplier immaturity)
Misleading design	Available knowledge not reused
Underestimated environment effect/influence (e.g. material deformations)	Insufficient user requirements research

As said, design errors are rarely traceable to one root-cause (Chao et al., 2001). However, with the given limited availability of error occurrence data, the failures were classified under one category which seemed most applicable. As such, the analysis is based on "best assumptions" to give an overview where the majority of errors accumulate. To validate the results, the qualitative data on process drawbacks was analysed in order to create connection between the findings.

Thus, the information from interviews was used to map process deficiencies and link them to the DERC areas. The elicited interview statements were clustered using the KJ method to answer the question of "Why do design errors occur in the Philips development process?". The main groupings are shown in fig. 4.2.

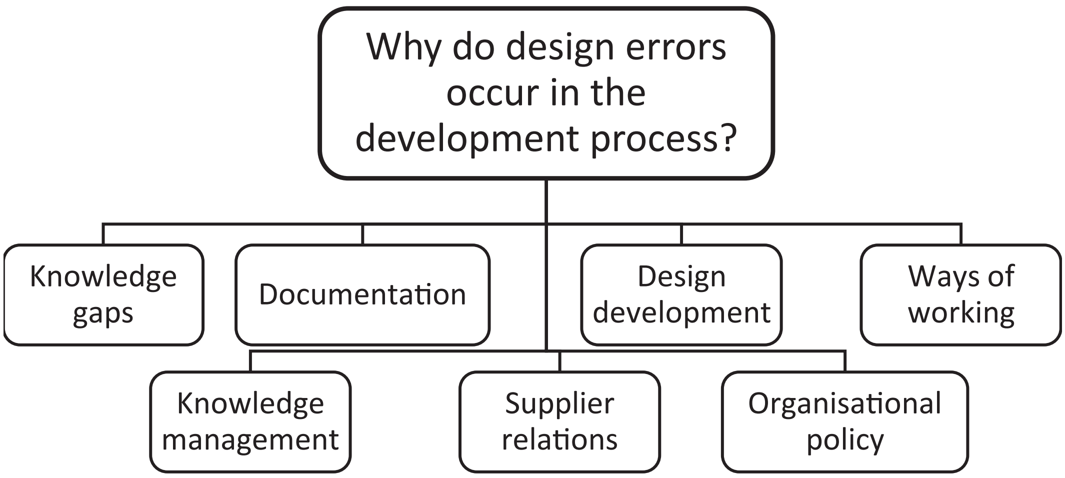

Figure 4.2: Clustering of process deficiency areas

By assessing the frequency of the statements under clusters, major drawbacks were identified for further analysis with the 5WHY method to determine their root-causes. The problem statements are shown in fig. 4.3 and linked to the development project influential categories to map them along the analysis. The main drawbacks were in relation with knowledge management and design task communication which indicates problems at the organisational level. A lot of issues brought up during the interviews referred to lack of standardised ways of working and sporadic practices in project execution which affect the success of projects. This gave grounds for having the "organisation" root-cause branch as part of the analysis of the qualitative data as the organisational situation could be assessed through interviews.

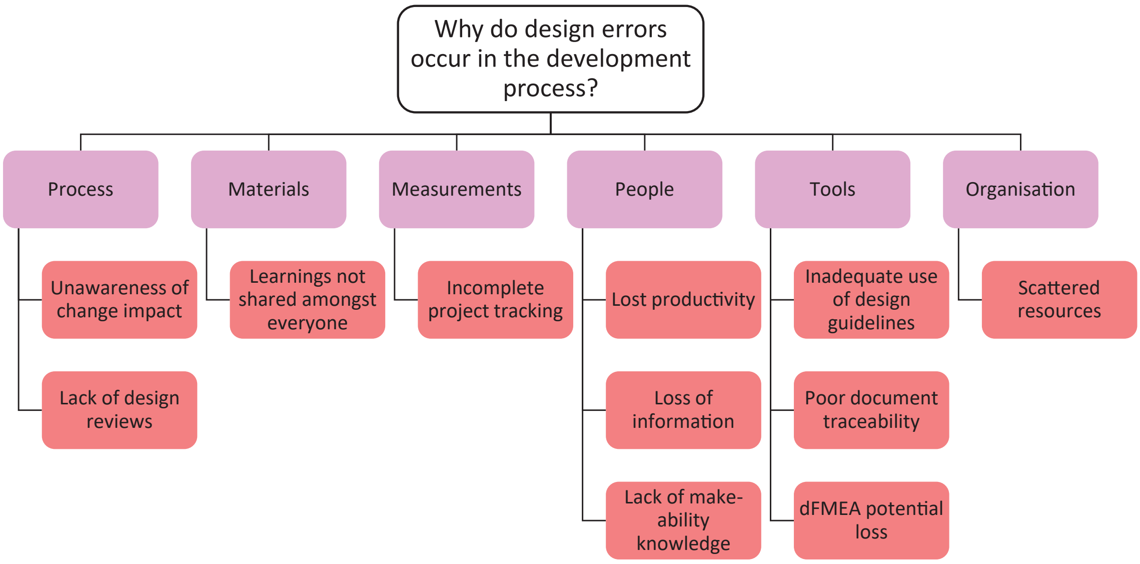

Figure 4.3: Major drawbacks in the development process *(colour-coded)*

The 5WHY process was conducted with the available information from the interviews and additional discussions with the developers to understand the underlying issues of current ineffective practices and ways of working. Each identified problem resulted in multiple root-causes which is common for design process errors. These were classified under the same categories of the DERC model to figure out which areas are in need of improvements and should be emphasised during the counter-measure development. An example of the analysis is shown in fig. 4.4 and the full outcome in Appendix C.

The encountered problems and determined root-causes were common development process issues across industries. The lack of knowledge gaps' visibility, change effect in systems and under-defined functional relationships are reoccurring deficiencies in development teams (Gustafsson et al., 2016; Ward and Sobek, 2014). As well as mounting rework due to early decisions without adequate knowledge or information loss and inefficient knowledge reuse which largely contribute to exceeding budgets

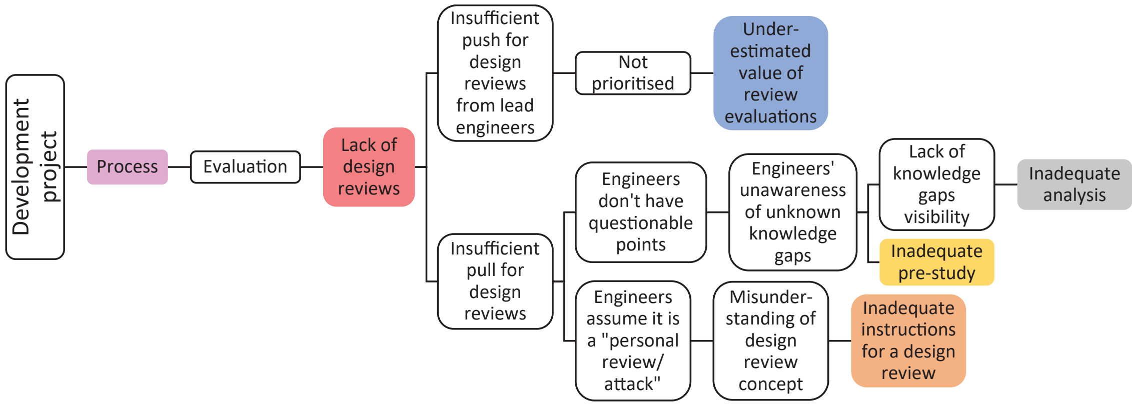

Figure 4.4: Example of 5WHY analysis process *(colour-coded)*

(Kennedy et al., 2014). These tendencies have been observed from complex to incremental development projects which have surfaced with shorter time-to-market cycles and increasing frustration of development engineers (Hoppmann et al., 2011; Ward and Sobek, 2014; Khan, 2012).

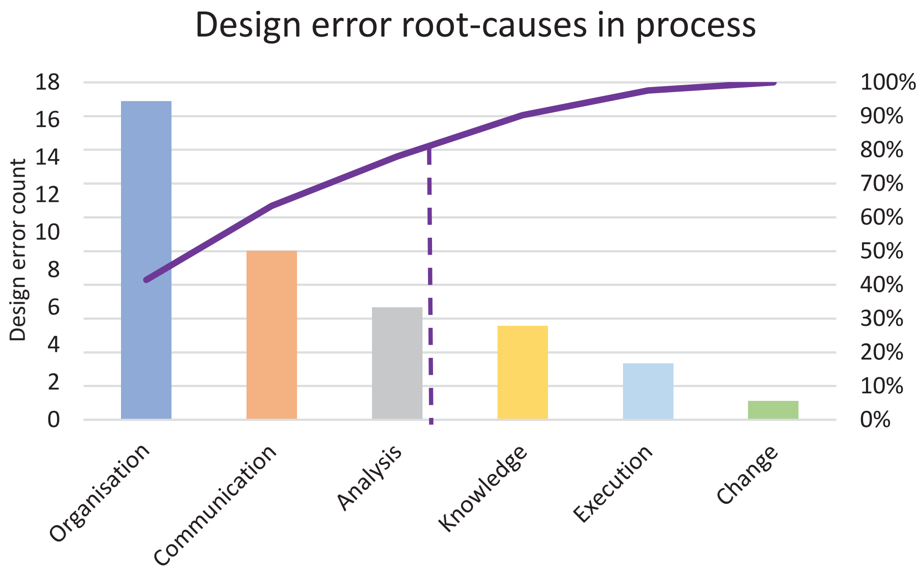

Figure 4.5: Design process and design error root-cause relation *(colour-coded)*

An overview of the findings is presented in fig. 4.5. Now the "vital few" categories were shifted towards "organisation", "communication" and "analysis" which go in line with the observations from other industries. The transformation to mounting "organisation" root-causes is not surprising as with the increased availability of qualitative data design errors could be tied to many causes as well as create the understanding of the organisational environment's influence which was previously omitted from quantitative data analysis. This validates the considerable affect of organisational principles over the success of the projects and the depth of the problem at hand. The category involved “incomplete knowledge management system” and “underestimated value of capturing learnings/giving guidance” etc. These are in strong connection with communication principles which explains the emergence of the category up front. The root-causes included “incomplete instructions/guidelines” in various tasks. The organisational policy and communication deficiencies were better addressed through interviews as these created an understanding of ways of working and its effect on design process errors. As previously stated, the quantitative data only gave basis for “assumptions” on where the design error root-causes lie.

Moreover, the previously identified “analysis” and “knowledge” DERC categories are still part of the “vital few” as they strongly relate to organisational deficiencies and multiple actors in relation generate design errors. This relation indicates the need for organisational process improvements to align standard working ways and establish a common culture for the development team through better communication principles and tackling knowledge management establishment – also implied by interviewees – to solve the problem.

The currently available tools were partially developed which leaves room for advancements and incorporating “lean principles” step by step. The majority of the PDM group was not using many lean tools but had had training in “lean innovation” which had sparked awareness of improvements and interest in change. Furthermore, even though knowledge was primarily shared through face-to-face communication – which is considered as the best principle (Ward and Sobek, 2014) – without any knowledge management or documentation of it, it gets forgotten and disregarded as no evidence is available.

4.2 Improvement Areas

From the process analysis and linkage between design error root-causes to deficiencies, more explicit improvement areas emerged within the development project structure. Thus, the directions for countermeasure development were determined based on the categories of the Fishbone, shown in fig. 3.2, and root-cause category relation to mitigation objective to conclude the analysis with both models.

The fig. 4.6 depicts the overall process improvement areas in relation to “organisation”, “communication”, “analysis” and “knowledge” DERC categories, colour-coded as in fig. 2.5. These were hand-in-hand with the inefficiencies studied by many researchers, like Kennedy et al. (2014); Ward and Sobek (2014); Khan et al. (2013) to name (only) a few, from the observations in other or related industries.

Identified advancement areas are represented solely – for better research guidance – but aim to benefit and enhance one another for a combined effect. For example, the “develop decisions based on facts mentality” relies on a better knowledge and documentation build-up for generating applicable factual data for decision making.

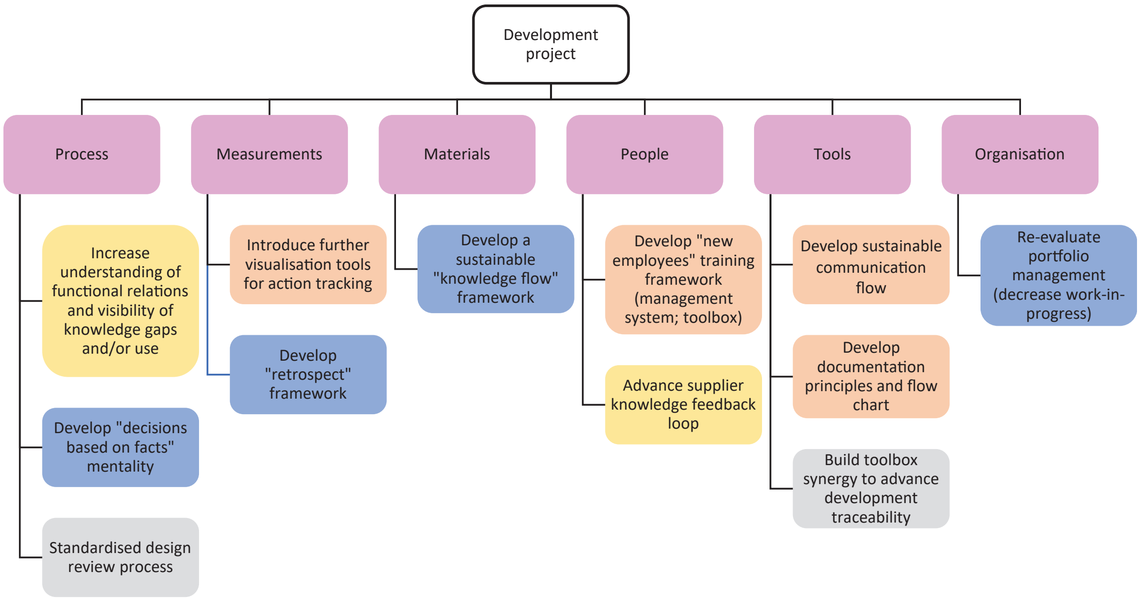

Figure 4.6: Identified improvement directions *(colour-coded)*

5

Theoretical Framework

The literature study was conducted to assess the current state-of-the-art best practices in product development process models. As the identified improvement areas were observed by researchers and practitioners across industries, the "conventional methodology" has been challenged with new directions for DPEP in order to mitigate the inefficiencies (Kennedy et al., 2014; Ward and Sobek, 2014; Oosterwal, 2010). This has led the practice towards lean product and process development (LPPD) framework which is proposed as the most effective countermeasure for described root-causes in chapter 4 and for high performance product development (Hoppmann et al., 2011; Khan et al., 2013).

The main shift in product development methodology is moving from a point-based concurrent engineering (PBCE) approach to set-based concurrent engineering (SBCE) which has shown most effect in rearranging development systems for increased quality output (Kennedy et al., 2014; Ward and Sobek, 2014). As SBCE is considered part of the LPPD framework, guiding the research towards the "lean thinking" direction for solving the problem at hand seemed most fruitful.

Although the initial framework on LPPD already emerged around 20 years ago with studies of the Toyota Development System (Sobek et al., 1998), there is still a gap in validating the success of these practices in other industries (Khan, 2012; Schuh et al., 2008). In addition, there are different models of the lean framework given the origin of studies – such as implementing lean production system mentality to development of or incorporating "lean thinking" in the development process by creating new methodology as observed by Khan et al. (2013). Thus, recent studies have tried to package the LPPD to reach consensus on the base model (Khan, 2012; Hoppmann et al., 2011; Ward and Sobek, 2014).

Furthermore, research has driven the case studies of implementing the "lean enablers", for example gathered by Oehmen (2012), in different organisational environments and development fields to verify the positive impact of these approaches. The enablers vary from applying SBCE (Kerga et al., 2014; Araci et al., 2016; Khan, 2012; Oosterwal, 2010), which is a large-scale change, to new reporting templates, such as A3 (Stenholm et al., 2015), or other process improvements inspired by lean (Tortorella et al., 2015; Vinodh and Kumar, 2015). As many have shown promising results – both by research projects and practitioners themselves (Stenholm et al., 2015; Oehmen, 2012; Oosterwal, 2010) – the countermeasure development for the BG Coffee development department was also focused for contributing to the LPPD research field. Thus, different "lean enablers" were studied according to the improvement areas to build the DPEP framework. Other conventional directions were not thoroughly investigated as these practices were known to the organisation and established to some extent. As such, in order to challenge and refresh the process, advancements of traditional approaches and lean methodology were prior focus.

5.1 Lean Product and Process Development

"Lean thinking" mainly focuses on value – to create a process flow with minimal waste (Ward and Sobek, 2014; Khan et al., 2013). It translates into defining waste and eliminating it from the process which in development is tightly related to knowledge. Ward and Sobek (2014) describes three main knowledge waste categories: scatter (communication barriers, poor tools), hand-off (useless information, waiting) and wishful thinking (testing to specification, discarded knowledge). These observations are common in "conventional" development structures which result in rework and defective products as decisions are made based on inadequate information. This in turn creates delays and increased development cost (Kennedy et al., 2014).

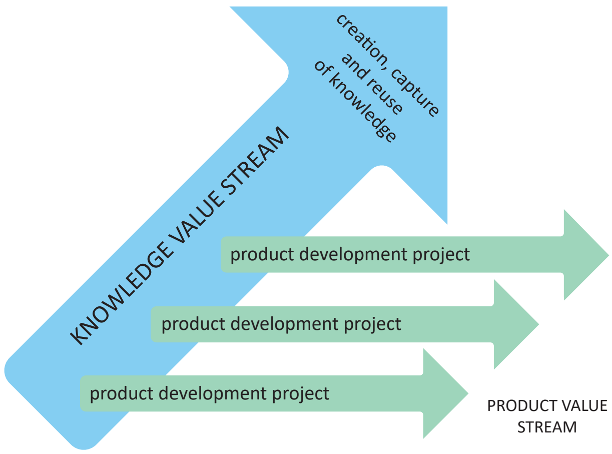

Figure 5.1: Lean innovation knowledge and product creation value stream (Kennedy et al., 2008)

Thus, LPPD is built-up on a knowledge value stream (Kennedy et al., 2008), shown in fig. 5.1, to create a high performance product development system. It translates to front-loading the development project with fast knowledge creation cycles and delaying decisions to minimise rework and costly changes in the end of the project (Kennedy et al., 2014; Ward and Sobek, 2014; Morgan and Liker, 2006). The approach supports the DPEP purpose to reduce design errors in development which affect the customer value and the cost of the project (Chao and Ishii, 2004). In the LPPD framework it is achieved by implementing SBCE (Sobek et al., 1998; Ward and Sobek, 2014).

Figure 5.2: Conceptual LPPD model (Khan et al., 2013)

In order to reach the SBCE development model, other building blocks need to be in place for support. Khan et al. (2013) proposed four organisational enablers, shown in fig. 5.2, for the SBCE: "value focused planning and development", "knowledge-based environment", "continuous improvement culture" and "chief engineer technical leadership". These align with the ideas of Ward and Sobek (2014) who present five major principles for LPPD as "value focus", "entrepreneur system designer", SBCE, "cadence, pull and flow" and a "team of responsible engineers". They also align with the four critical elements of Kennedy et al. (2008): SBCE, "system designer entrepreneurial leadership", "responsibility-based planning and control" and an "expert engineering workforce". Additionally, Morgan and Liker (2006) emphasised the same values and Hoppmann et al. (2011) found altogether eleven contributing factors which were partly broken down into detail from the mentioned ones which resulted in a higher number.

The model introduced by Khan et al. (2013) best describes the cultural organisational change needed for a new development system build-up as it is modelled in the perspective of reaching the SBCE system implementation. It was used as the base for developing the process flow for the BG Coffee development department. The model only fails to emphasise the necessity of the involvement of a responsible and knowledgeable team which should be a separate building block as well. The tools – which are considered as "lean enablers" in the literature – supporting the framework are discussed in the following sections regarding their relation to mitigating the identified DERC.

5.2 Knowledge and Communication

As stated, LPPD is considered to be a knowledge-based approach (Ward and Sobek, 2014; Kennedy et al., 2014) and emphasises the need for developing and reusing knowledge for high performance product development (Hoppmann et al., 2011). Knowledge management is cumbersome for many organisations as it is regarded as time-consuming and the established process often does not create a sustainable flow (Maksimovic et al., 2014). Many companies have implemented a knowledge management database or a deliverable of retrospect – capturing lessons of a completed project – but find the information available unused (Hicks, 2007; Maksimovic et al., 2014). This might be due to the information being too specific or too general, as the guidelines and formats are not aiding the engineer, or the knowledge is gathered only at the end of the project. Also, the most valuable – tacit knowledge or know-how – is hard to communicate in the form of an information document. On the other hand, the explicit knowledge – which is created in the form of data and facts which is easy to transfer – results in over-excessively detailed information (Tyagi et al., 2015; Lindlöf et al., 2013). Moreover, the database systems are often hard to navigate as the available information is poorly structured and not refreshed. As such, the practices are usually neglected even if the overall benefit of capturing learnings is understood by the actors (Chao et al., 2001; Hicks, 2007).

Thus, the LPPD framework has introduced tools – trade-off curves and checklists – which are visual and concise living documents (Maksimovic et al., 2012; Lindlöf et al., 2013; Tyagi et al., 2015). The main principle of the methods is to incorporate these along the entire process as the knowledge capturing and use is part of the development structure and not a separate task (Ward and Sobek, 2014; Morgan and Liker, 2006). It facilitates continuous revision of the documents and makes use of visualising most of the information which is proved to be the most effective communication manner (Lindlöf et al., 2013; Stenholm et al., 2015).

5.2.1 Trade-Off Curves

Trade-off curves (TOC) are considered as one of the most powerful LPPD tools to create (re)useable knowledge (Ward and Sobek, 2014; Maksimovic et al., 2012; Lindlöf et al., 2013). Ward and Sobek (2014) have even stated:

"If I could teach you only one lean tool, trade-off curves would be it."

It is a basic way of visualising knowledge of performance attributes' relation in order to evaluate alternative concepts and optimise the design. The value behind using TOCs is to develop understanding of compromises in product performance, customer value and/or cost. As such, it facilitates creating knowledge and decision-making based on facts.

A TOC is created on gathered data about the defined relationship, for example a tube design characteristic and its manufacturing cost (Araci et al., 2017) or a comparison of different fasteners on a mating surface area and torque characteristics (Ward and Sobek, 2014). Its main representation is a graph, illustration in fig. 5.3 which showcases a TOC with a negative slope as the variables are maximised (or minimised) simultaneously. This gives the designer the ability to choose an optimal and balanced point on the graph to fulfill the product requirements (Stenholm et al., 2015; Ward and Sobek, 2014).

Another variation of TOCs is a limit curve which showcases the performance ranges – test to limits (breaking point). For example, different materials' behaviour may be compared by developing limit curves – how these withstand specific circumstances (Ward and Sobek, 2014). In addition, these can be used along with TOCs to define the feasibility of technology and map the design region to work with before narrowing down the decision to one point (Maksimovic et al., 2012).

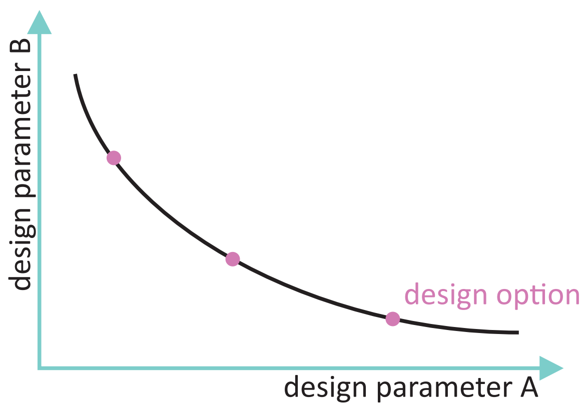

Figure 5.3: Trade-off curve illustration

Moreover, the curve is a good communication tool for concept development or exchanging capabilities and knowledge between different functions (Morgan and Liker, 2006; Ward and Sobek, 2014; Lindlöf et al., 2013). The standardised visual representation is easy to grasp for engineers and leaves little room for translation errors (Araci et al., 2016; Lindlöf et al., 2013).

The implementation of TOCs in various industries have showcased successful product development process improvements. Industrial case studies from the aerospace and automotive industry, conducted by Araci et al. (2017) and Stenholm et al. (2015) respectively, exhibited benefits of considering multiple alternative designs in parallel, minimised the need of resources by providing adequate knowledge for decisions and eliminated redesign loops and generated knowledge for future projects.

Araci et al. (2016) have developed a guide for a TOC creation, steps presented in table 5.1. They make a distinction between physics-based and knowledge-based TOC generation which both rely on real data sources compared to math-based TOC – algorithms and mathematical calculations for determining a possible outcome, mainly based on assumptions. The first two are considered applicable for LPPD framework as these involve proven knowledge.

Table 5.1: Steps for trade-off curve generation (Araci et al., 2016)

Step	Knowledge-based TOC	Physics-based TOC
1	Decision criteria	Understand the first design set
2	Data collection	Understand the physics of the product
3	TOC generation	Test and analyse
4	Feasible solutions	Compare the solutions of the design set
5	Optimum solution	Select/narrow down designs
6		Enhance design

Each step translates into specific activities. For example, in the knowledge-based TOC generation step 4 “feasible solutions” consists of three actions: “define the feasible and infeasible area”, “identify the design solutions within the feasible area” and “develop a set of potential design solutions”. This framework could be used as more of a process map/checklist after the method has been introduced to the process.

Ward and Sobek (2014) offer a more comprehensive guide for introducing the tool to engineers by organising three events/workshops. It involves determining the problem scope, examining causal factors to determine critical parameters and discussion on the developed TOCs, further described in table 5.2. Between the second and third event the data is gathered and the workshops are finalised with two implementation plans for the design fix and documenting the knowledge in a reusable form.

The data gathering involves finding already available testing information or setting up quick experiments. Also, the variables need to be combined in different ways to understand their relationship and define critical effects. The right combinations surface through try-outs and thus the TOCs need to be constantly refreshed and reviewed for improvements along the development process. A similar but less structured approach is also presented by Kennedy et al. (2014).

Table 5.2: Trade-off curve generation workshop (Ward and Sobek, 2014)

Event	**Action**
Define problem	Choose a single failure mode and identify related parts, manufacturing processes. Reduce data to a simplified A3 drawing.
Identify causal factors	Generate a causal diagram: root-causes of the failure mode. Cluster the factors and determine the most influential parameters. Assign trade-off curves.
Discussion of result	Critically evaluate the generated trade-off curves and data reliability/accuracy. Use it to evaluate the problem and generate applicable countermeasures. Assign design fix implementation plan and knowledge documentation plan.

The way of using TOCs in development has also received critique in relation to hindering innovation. The theory of innovation argues that accepting trade-offs restricts exploration and limits novelty (Kerga et al., 2014). However, lean practitioners also note that the trade-off curve is not a finite condition but constantly evolves and can be modified with new emerging technologies (Ward and Sobek, 2014). This should be one of the driving forces for development to also explore the trade-off curve, the whole design space and further push the limits for fostering innovative ideas.

5.2.2 A3 Reports

The A3 report is known as a lean communication tool which guides engineers to give clear and concise information (Morgan and Liker, 2006; Tyagi et al., 2015). The method itself is thoroughly described in section 2.1 as the template is used for the research design in the given thesis.

The main benefits are teaching engineers to filter and clarify their thoughts, have a communication guideline – which is easy to follow for different actors who are aware of the template – and its flexibility to be modified for different tasks (Morgan and Liker, 2006). It is mostly known for structuring problem-solving but can accommodate part design information, decision-making, proposals and also trade-off curves (Ward and Sobek, 2014). As it involves tacit and explicit knowledge as well as visualisation, it facilitates effective knowledge sharing (Lindlöf et al., 2013). Many researchers, like Maksimovic et al. (2014); Tyagi et al. (2015); Lindlöf et al. (2013);

Correia et al. (2015), acknowledge the A3 method as a simple communication tool and a “lean enabler”.

The positive result have been showcased by Stenholm et al. (2015) and Leipold and Landschoot (2009) for problem-solving and technical design reviews, respectively. The feedback has proven the tool to enhance discussion and understanding within teams as well as structuring the process. It also verifies the applicability of using the template for various tasks.

Leipold and Landschoot (2009) held a brainstorming session for identifying the relevant boxes for a design review A3. The study demonstrates the flexibility of a standardised communication tool which serves the creative freedom aspect of innovation. The main idea behind the A3 template should still aid a thorough learning cycle and gathering evidence/real data for decision making while engaging multiple parties (Shook, 2009).

From the implementation side, Stenholm et al. (2015) observed that recognising the benefits of using the A3 takes some time as there is a learning curve in understanding the process of generating the report. As such, the value of it is created by the user experience and developed skills on communicating the relevant information.

5.2.3 Checklists

The engineering checklists (or checksheets) are a well-known tool from the Toyota Product Development System as their main knowledge carrier. These are extensive documents – some over hundreds of pages – which include all the available information across functional departments of a given sub-system or part. Toyota uses them as sharing the current capabilities, updating knowledge and guiding the development work (Sobek et al., 1998). The main aim is to regularly review design decisions and assure a minimum quality level (Tyagi et al., 2015). These also function as a reminder for the designer as checklists are generally known in the industry. That is the difference between the Toyota understanding of a checklist and a conventional one – a checklist is not only a design guideline of a process reminder but acts as a knowledge document (Chao et al., 2001; Kennedy et al., 2008).

The checklists have been developed to such an extent and efficient use in Toyota due to the discipline to maintain and utilise the documents through-out the development process. Ownership is held by the functional level, i.e. by the people who are working on a specific part or sub-system, which makes revision and usage of the information part of the development task (Morgan and Liker, 2006).

However, checklists’ implementation and effects on improving the product development process are not well covered in research. Also, the available case studies are mainly from the automotive industry. One of them is by Catić and Malmqvist (2013) who present a method for creating a checklist for system integration.

The first stage involves a pre-study to determine where the checklists should be implemented. The second stage is the introduction of the method to the process based on the Ishikawa diagram model – defining inputs/outputs, mapping lead time and developing an initial guideline, shown in fig. 5.4. The third stage involves using the generated checklist and its continuously improving it.

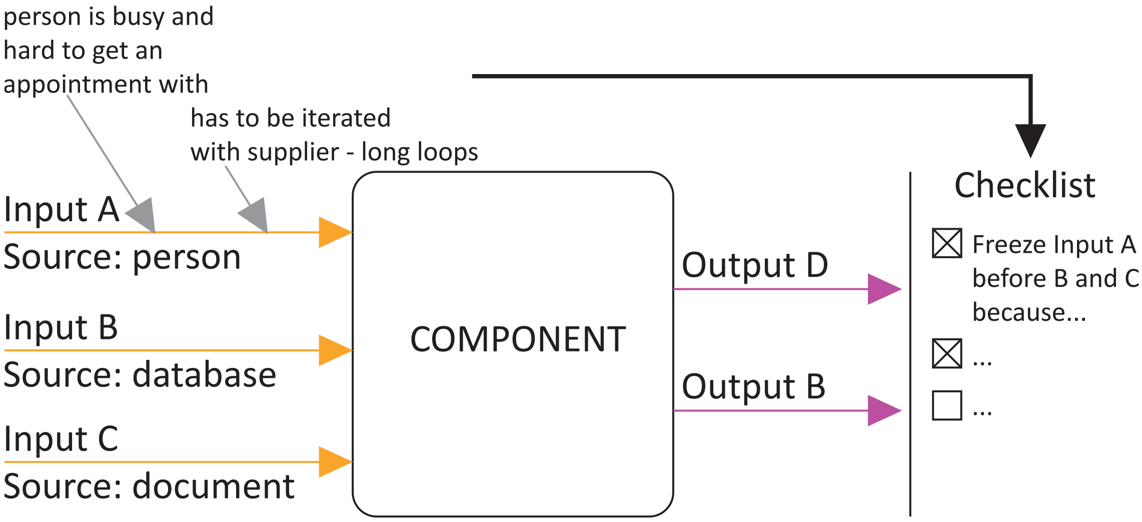

Figure 5.4: Model for creating a checklist (Catić and Malmqvist, 2013)

Catić and Malmqvist (2013) advise to let the designers generate the checklists, as they are most knowledgeable about the design process, and possibly align these with a Stage-Gate® process. The feedback from engineers was favourable as they thought checklists would benefit guiding the process and improve the quality of work.

Bilal et al. (2014) developed a design rule/checklist system for tool development inspired by the poka-yoke techniques – mistake proofing (Chao et al., 2001). The database system consisted of product and process phase specific rules which would guide the designer. It eased the parameter selection and reduced errors as well as introduced a systematic approach to gather and share knowledge. The critique of the method was that it should also include an option to input additional contextualised data to increase the value.

5.2.4 Innovation Classification Diagram

Product development projects are often poorly defined or scoped which leads to misguided design development (Chao, 2005). Khan (2012) developed an easy colour-coded visualisation method to communicate the level of innovation within a development project. It facilitates focus and understanding of the scope of the project as well as planned innovation effort. It is a simple system sketch with highlighted parts which will be improved in the project, example shown in fig. 5.5.

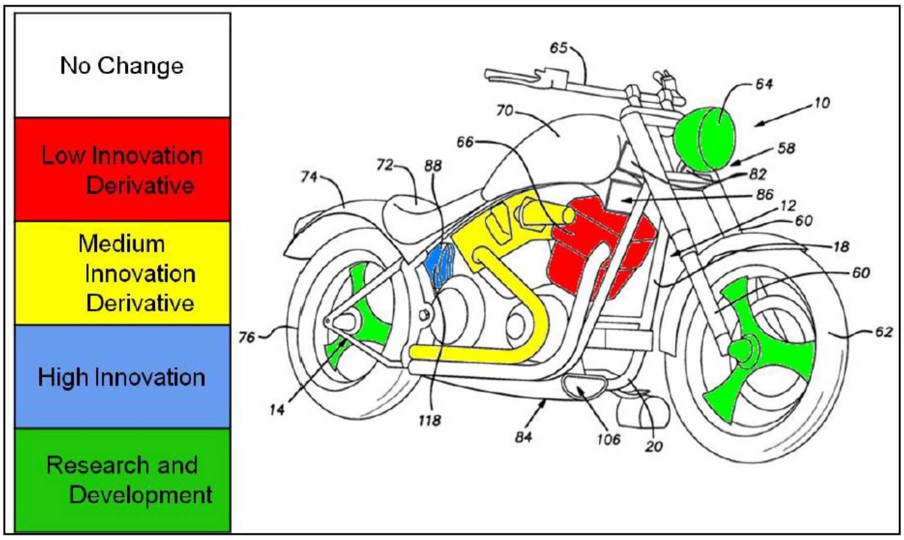

Figure 5.5: Innovation classification diagram (ICD) illustration (Khan, 2012)

Given the case studies done by Khan (2012), the method clarified the project priorities for designers and helped assessing the necessity of resources for execution, discussing alternatives and constraints. It was well received by both, engineers as well as project managers as a communication tool.

5.3 Analysis

Analysis tools for the design process can be categorised in two: detective, like design reviews which identify errors already made, and preventative methods (Chao et al., 2001). The latter try to mitigate errors before occurring which goes in line with the "lean thinking" as it reduces rework and eliminates waste (Morgan and Liker, 2006).

The preventative methods are also considered as guiding learning cycles by creating an understanding of the current situation through analysis. These are the building blocks for planning the development and aligning different actors for knowledge-based development (Gustafsson et al., 2016). These involve product composition and architectural relations build-up as well as risk management (Gustafsson et al., 2016; Chao and Ishii, 2004).

“Lean thinking” facilitates tools which are kept simple and actionable, meaning methods which do not create extra steps but can be easily incorporated into the development process and add direct value to the customer (Ward and Sobek, 2014; Kennedy et al., 2008).

5.3.1 Causal Maps

In order to create better understanding of the system and its functional relations, system decomposition and causal diagrams are used to visualise and analyse interactions within the developed product (Gustafsson et al., 2016; Levandowski et al., 2014). It is also intended for knowledge gaps visibility and determining critical attributes to prioritise design decision as well as assess design change impact (Ward and Sobek, 2014; Levandowski et al., 2014; Ahmad et al., 2013).

Causal diagrams are simple representations of properties’ relations – interaction or dependencies and their nature. It is a transparent visual tool to analyse and communicate system level design (Gustafsson et al., 2016). Usually the characteristics are connected through arrows to show the interplay and a positive or negative sign depicts the effect as shown in fig. 5.6.

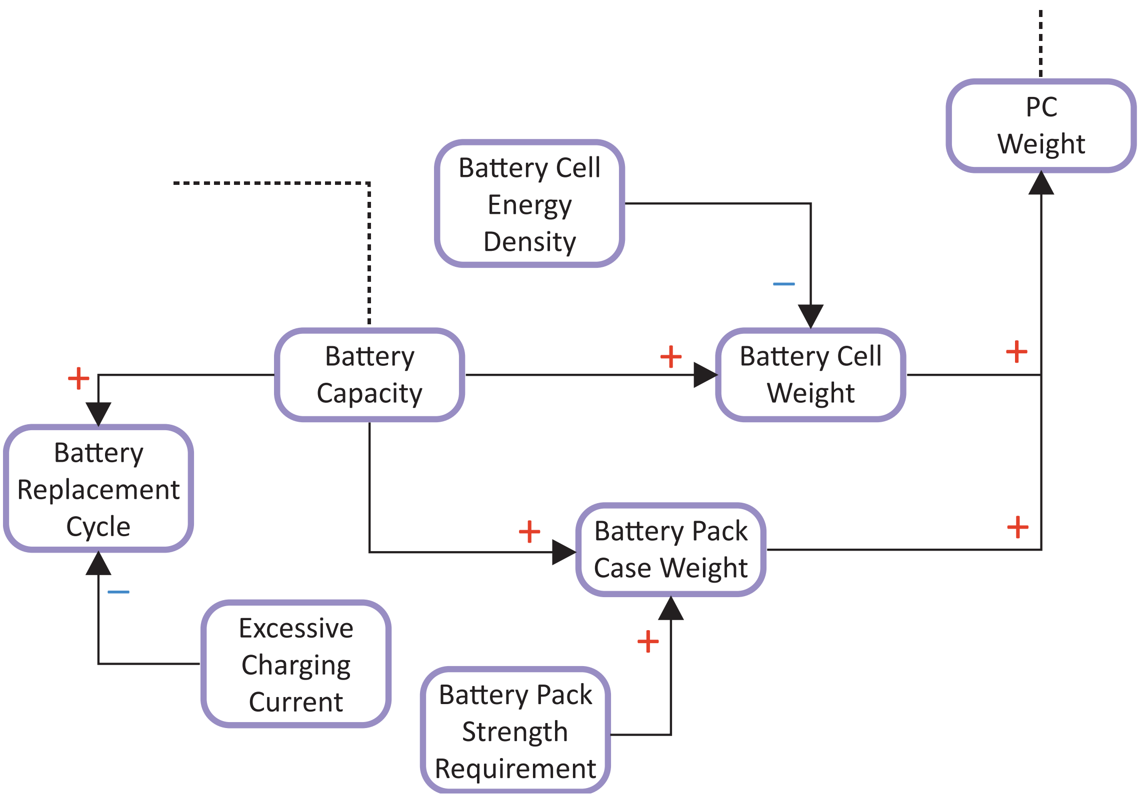

Figure 5.6: Part of a causal diagram adapted from Gustafsson et al. (2016)

Causal diagrams could be used in relation with trade-off curves, discussed in section 5.2.1. The diagram can be the starting point of defining the trade-offs in product performance by determining the cause-effect chain and the impact of different design parameters. As such, it may guide the decision-making and understanding of needed additional knowledge (Ward and Sobek, 2014). Together these form a base for knowledge capturing and sharing (Gustafsson et al., 2016).

In addition, causal maps can be created with added requirements and function structures, like the function tree and the chromosome model (Malmqvist, 1997; Ahmad et al., 2013). These serve the synergy of multiple tools for increased value output. Many of the methods developed for such integration of tools need a lot of detailed input or computations, like parameter-based models (Ahmad et al., 2013) and DEMATEL methodology (Wu and Tsai, 2011) respectively, which are often not available or too resource heavy in new product development. Thus, these are more focused on assessing change impact (Ahmad et al., 2013).

However, the principles of how to structure the different aspects in relation to one another are still valuable. Ahmad et al. (2013) present a systematic approach for combining/analysing product knowledge as an information structure framework (ISF). It comprises four layers described in table 5.3.

Table 5.3: Information structure framework (Ahmad et al., 2013)

Layer	**Description**
Requirements	Specification mapped on functions (each requirement needs to address at least one function), traceable for design.
Function	Decomposition of product functions, may include a network of flows (energy, material or signal).
Component	Participate in realising at least one function. Interconnection between components represents immediate physical interaction.
Detailed design process	Design parameters associated with components – an information processing network of tasks interconnected by parameters (identify dependencies, sub-sequences).

Determining the value of developing interaction and cause-effect chains are always subjective to the level of detail. As such, it is suggested to start addressing the most influential or unknown areas to identify critical design decisions and work the decomposition downward according to the development needs (Gustafsson et al., 2016). In order to keep it condensed, it is advised, for instance in the ISF model, not to go further than 50 components (Ahmad et al., 2013).

5.3.2 Quality Function Deployment and TRIZ

"Lean thinking" facilitates front-loading the development process and creating value for the customer – thus, the product definition is an important part of delivering successful projects (Ward and Sobek, 2014). Quality Function Deployment (QFD) is a well-known tool for translating the "voice of the customer" (VOC) to the design requirements. It is a structured method for product planning and design through defining four relation matrices from VOC to production planning (Chao, 2005), shown in fig. 5.7. Vinodh and Kumar (2015) have applied QFD in a lean framework to create a better customer value translation into products. In the given case study of minimising development time, the individual effect of implementing QFD was not discussed but was part of future state suggestion together with other changes.

However, QFD has not been considered as a "lean enabler" as it has shortcomings in being based on assumptions or subjective judgment and having a poor effort-value balance. Employing QFD is considered quite time-consuming and does not clearly define the innovation direction (Chao, 2005; Kerga et al., 2014). Thus, Kerga et al. (2014) have proposed QFD in relation with "Theory of Inventive Problem Solving" (TRIZ) to support lean development.

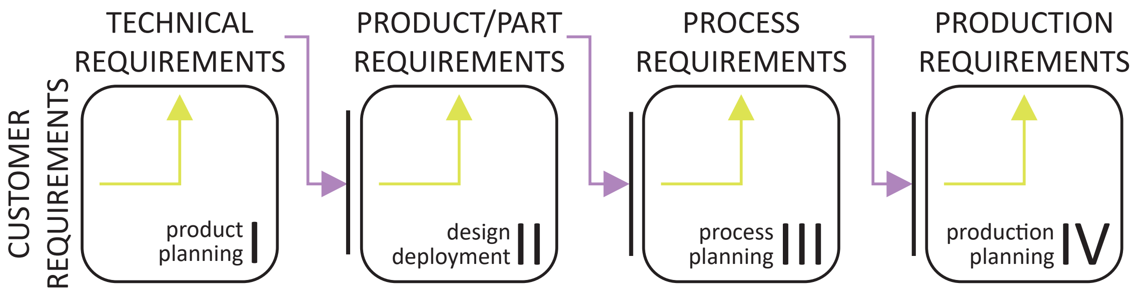

Figure 5.7: Quality function deployment flow (Chao, 2005)

TRIZ is based on generating innovative concepts through solving contradictions (i.e. trade-offs). It facilitates systematic innovation through notions that many of the engineering problems faced during development are already solved in another industry in a different situation and there are predictable patterns of technological change which help determine the most probable successful next steps. The method has shown an increased rate of developing patentable ideas as its principles where constructed upon an extensive patent research (Ullman, 2010).

Together the two methods complement one another as QFD helps to determine the contradictions and prioritise these according to customer value while TRIZ guides the innovation phase (Kerga et al., 2014). Thus, it aids a clear understanding of critical product design and customer value relation while favouring innovation.

5.3.3 Failure Modes and Effects Analysis

Another way to address project pitfalls and prevent rework is to apply risk management tools. Failure Modes and Effects Analysis (FMEA) is a preventative analysis tool in order to determine possible product failures. As such, it helps to identify, prioritise and take action on potential problems or critical aspects of the developed product (Chao and Ishii, 2007). The process involves identifying possible failures to meet requirements or realise functional performance which are scored with probability of occurrence, severity and detection to calculate the risk priority number (RPN). Then actions are assigned according to the rating in order to prevent critical situations (Ullman, 2010).

The method is broadly applied in development processes across industries which has led to identifying many shortcomings of the tool. These include using FMEA too late in the process, performed as “box-checking”, being subjective as depending on the experience of the team and being too time-consuming (Chao and Ishii, 2007).

Ward and Sobek (2014) also discuss the quality of FMEA. A process value assessing flow-chart is used to understand the benefits of the tool as well as parts which should be modified. Thus, the FMEA should not address the probabilities of failure – which are in their nature only assumptions – but rather understand the root-causes of failure in order to eliminate them not only minimise the effect. The difference in questions to focus on is given in table 5.4.

Table 5.4: FMEA focus shift (Ward and Sobek, 2014)

Conventional FMEA	**Modified FMEA**
How can the product or process fail?	How can the product or process fail?
What is the probability of each failure?	What causes the failure?
How serious are the consequences?	Under what circumstances will the product fail?
What is the plan to prevent or detect possible failure?	What design circumstances will prevent the failure?

The shortcomings have spun other advanced and modified FMEAs as well, like scenario-based, automated and life-cost versions to name a few (Chao and Ishii, 2007). Chao (2005) has developed a design process FMEA in order to mitigate the dependency on the experience of the team and create understanding of their own possible failures due to lack of knowledge or ways of working. It aids in preventing design errors which are specific to each project.

The approach involves going through the design process tasks and addressing the six DERC categories to identify likely errors. The process is supported by sets of questions to help the team remember relevant aspects to cover, examples are shown in table 5.5. Then the errors are rated, prioritised and recommended actions assigned. The outcome can be modelled in a checklist version to guide design work.

The method takes another perspective on evaluating the process pitfalls and fostering awareness of the team capabilities. Thus, the analysis helps to address the knowledge gaps and define design tasks for engineers which aligns with the LPPD framework (Ward and Sobek, 2014; Catić and Malmqvist, 2013).

Table 5.5: Examples of design process evaluation guiding questions

	Knowledge
1	Has there been previous work in this area?
2	How is previous work shared?
	Analysis
1	How does this task affect the rest of the system?
2	What are the input, output and noise factors of this work?
	Communication
1	How does information flow between tasks?
2	Will there be collaboration with other parties?
	Execution
1	How do the users know how to perform this task (guidelines, documentation)?
2	What tools are used to complete the task?
	Change
1	Can the results of the task be changed at a later time?
2	How sensitive is this task to noises from or changes made in other tasks?
	Organisation
1	Is there a strong structure to the process?
2	Are design reviews scheduled?

To generate questions more relevant for the organisation, a design error database should be put in place to analyse where design errors occur and what are their root-causes. This data would help to understand which areas need more effort or large-scale changes to mitigate errors (Chao, 2005). In addition, the improvement initiations would be based on real data to drive the organisation forward and not allow to ignore process deficiencies.

Addressing the design process analysis in order to emphasise the importance of reliability, availability, maintainability and supportability (RAMS) has been prioritised by other risk analysis researches as well, such as Markeset and Kumar (2003). This goes in line with the "lean thinking" of advancing the process of delivering value by designing quality products (Ward and Sobek, 2014).

5.4 Organisation

The LPPD framework comprehends organisational level change as the whole cultural environment and development set-up is modified to aid lean innovation. This indicates the need of managerial support and building new values and/or re-evaluating priorities of the organisation – a mindset shift (Ward and Sobek, 2014; Kennedy et al., 2008).

The best way to initiate improvements is to lead by example, hence the leaders have to be aligned in order to create a favourable setting for "lean thinking" establishment (Schuh et al., 2008). To assist change, they have to develop understanding of the LPPD framework and its benefits in order to translate their beliefs through mentoring and training of their staff. This is the core of a successful change in an organisation as it is a continuous effort (Khan et al., 2013; Ward and Sobek, 2014; Lindlöf et al., 2013). The remodelling of "organisational thinking" is accomplished in small steps by driven and relentless "lean leaders" who help to identify and eliminate waste in order to create effective value streamed processes (Mascitelli, 2011; Oosterwal, 2010).

5.4.1 Value Stream Mapping

As the main principle of lean is to eliminate waste for maximised value creation, the first step for initiating change is to evaluate the current state. Value stream mapping (VSM) is an approach to identify development process' wastes by mapping the current sequence of tasks and evaluating their value creation ability (Vinodh and Kumar, 2015; Schuh et al., 2008). It is best executed by involved stakeholders themselves who are aware of the process. For example, the detailed development should be arranged by designers. This gives the starting point for improvements and showcases the inefficiencies of the current system (Ward and Sobek, 2014). In order to advance the process, tools like the Design Structure Matrix (DSM), developed by Denker et al. (1999), and flexible process standardisation can be used.

DSM is a development project planning method which tries to eliminate iterative loops of rework. It is a matrix, illustration in fig. 5.8, of development tasks to analyse their dependency and which sequence results in the shortest cycle-time. It aids concurrent design and visualising project process (Denker et al., 1999; Kennedy et al., 2014). This is also the fundamental principle used in the Lean Scheduling system developed in Philips (Radeka, 2013).

	task A	task B	task C
task A	1		X
task B	X	2	
task C		X	3

Figure 5.8: Illustration of the initial DSM matrix (Denker et al., 1999)

For standardisation, identified reoccurring tasks and phases can be executed through the usage of common tools and guidelines – introduced in previous sections – which do not overregulate the process but lower the variability and support creative design efforts (Hoppmann et al., 2011). It also involves accompanying engineers with a standard toolbox for realising design tasks which have a clear input and output definition for ensuring baseline quality (Ward and Sobek, 2014).

5.4.2 Leadership

To create a change environment, management has to support improvement actions and guide these on functional level. In LPPD, the most important task for leadership is to develop "responsible experts" of subordinates through mentoring (Ward and Sobek, 2014).

As such, coaching and learning by doing is essential in a lean framework to create the building block of a knowledgeable and responsible team. Every leader becomes a teacher – not a commander – as the employees are trained towards methods rather than results (Lindlöf et al., 2013; Morgan and Liker, 2006). It involves investment to subordinates' education and hands-on personal coaching to facilitate transferring tacit knowledge (Tyagi et al., 2015). The main goal is to build ownership and responsibility of action into task execution as the supervisors avoid making decisions for their subordinates but try to teach them reaching solutions on their own through problem-solving techniques and creative thinking (Ward and Sobek, 2014).

Furthermore, the aim is to keep a standardised skill-set fresh and common across the organisation. The standard skills ease coordination effort as engineers know what is expected of them. For example, in Toyota managers also teach engineers how to prepare for meetings, interpret and create reports to promote coordination and clear communication (Sobek et al., 1998). In addition, they encourage engineers to stay within the same functional field to grow expertise career paths and become knowledgeable system engineers (Hoppmann et al., 2011).

In addition, the LPPD considers having a strong technical leader as one of the main success factors in product development (Hoppmann et al., 2011; Tyagi et al., 2015). The concept is known as the role of “the chief engineer” who is described as a heavyweight project manager. This position involves coordinating the entire development effort from understanding the VOC to delivering a quality product to the market (Lindlöf et al., 2013). “The chief engineer” has acquired technical skills to design and conceptualise the system architecture. Moreover, they need to persuade their team of engineers to realise the vision as they have no direct authority over the functional employees (Sobek et al., 1998).

The main principles in lean leadership is to help the development along domains of process, project execution, managing resources and problem-solving when necessary as managers have a more holistic view of the system than front line developers. However, the idea is to lead efficiently by improving the workers skills as described before, so leaders should rather ask and discuss more than model (Ward and Sobek, 2014). They set the behavioural example of “lean thinking” in the organisation by showcasing clear communication, visibility and knowledge across functions, respect for others and value creation. This led Ward and Sobek (2014) to give a guide, described in table 5.6, for creating internal discipline in an innovative environment which facilitates innate motivators. It presents the principles of “learning by doing” as an approach to teaching one’s sub-ordinates.

Table 5.6: Internal discipline guidelines (Ward and Sobek, 2014)

	Principle
1	Clear, distinct and complete areas of responsibility.
2	The opportunity to take direct action to accomplish those responsibilities through their own work (ability to develop designs, analysis and knowledge on their own).
3	The knowledge required to decide to make a decision and execute on actions (build knowledge repositories).
4	Objective, direct-from-reality feedback on how well their decisions work out (evaluation on performance measures).

5.4.3 LAMDA

The LPPD improvement culture is built on learning cycles which continuously provide more value and knowledge for the company. The cycle is an advancement from PDCA known as LAMDA which stands for look-ask-model-discuss-act. It is an active iteration, depicted in fig. 5.9, to effectively see, understand and dialogue better in order to add value (Ward and Sobek, 2014; Khan et al., 2013).

It is the core of guiding continuous improvement and problem-solving. The steps are described as following:

- Look – go-and-see, obtain first-hand information of the problem/situation
- Ask – gather relevant data by asking why (5WHY approach), deep dive to root-causes
- Model – visualise the situation as understood, develop countermeasures
- Discuss – communicate findings, gather evaluations/insight
- Act – realise the suitable countermeasures

After completing the cycle, it is time to “look” again to follow-up on the effect of the action and find new improvement areas (Ward and Sobek, 2014).

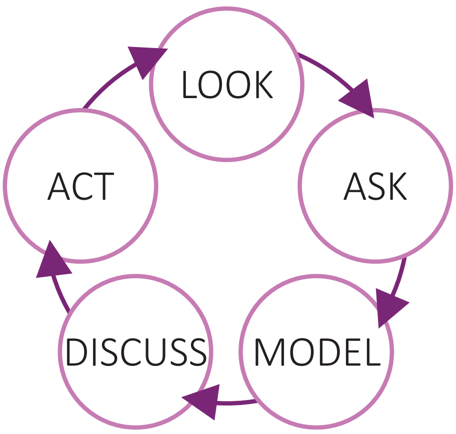

Figure 5.9: The learning cycle LAMDA (Ward and Sobek, 2014)

The learning cycle helps to develop the mindset of gathering knowledge and real facts rather than relying on gut-feeling. It also encourages to engage people close to the problem and communicate lessons for better and more sustainable realisation of improvement actions (Stenholm et al., 2015).

5.4.4 Set-Based Concurrent Engineering

Set-based concurrent engineering (SBCE) was introduced largely by the work of Ward and Sobek (2014) who studied the Toyota Product Development System.

As previously stated, the initial research and analysis was published already two decades ago (Sobek et al., 1999). This was the countermeasure for wasteful point-based development model (PBCE) which created a lot of rework and delivering products based on “best assumptions” with the design-build-test cycle (Kennedy et al., 2014).

The new approach, depicted in fig. 5.10, turned the cycle around into a test-design-build model which facilitates knowledge growth and decisions based on facts (Ward and Sobek, 2014). The fundamental idea is to break the product down into subsystems which can be concurrently explored in sets of alternatives within the given performance range. The variety of concepts is narrowed down through intensive testing which means that the proposal can be discarded only based on real evidence of its infeasibility. As such, the decision on freezing design parameters is delayed until a feasible design space is identified in order to find the most optimal design with the combination of still available alternatives (Ward and Sobek, 2014; Khan et al., 2013; Kennedy et al., 2014). This is the main difference with PBCE where the concept is freezed in the beginning and concurrent development is realised through simultaneous detailed subsystem design given the determined parameters (Endris et al., 2012).

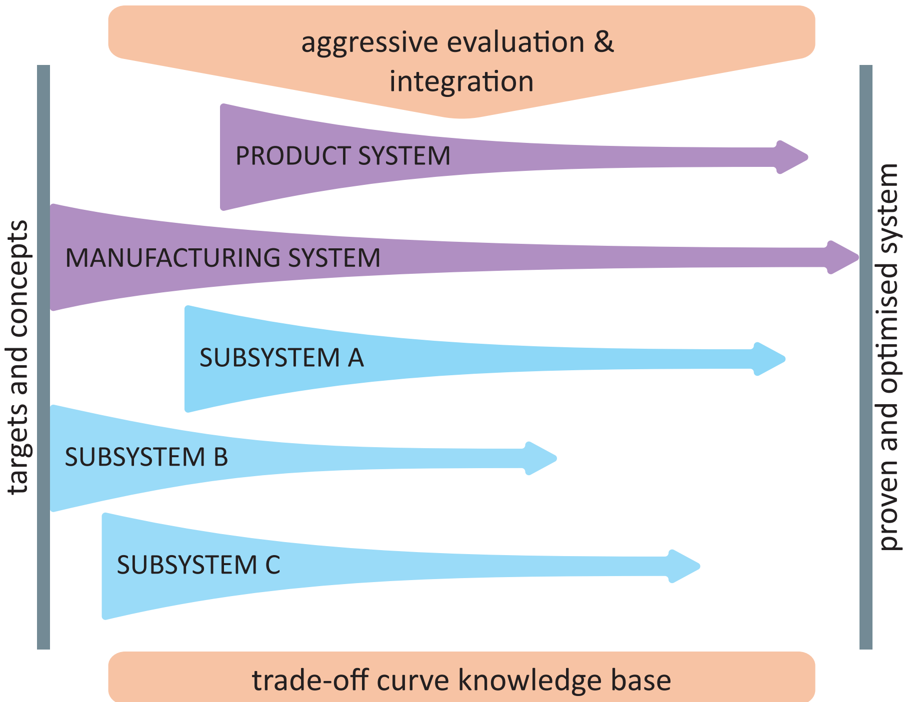

Figure 5.10: SBCE model (Ward and Sobek, 2014)

SBCE front-loads the development process with multiple knowledge creation cycles which aids creative experimentation and having a larger design freedom for exploration (Endris et al., 2012; Ward and Sobek, 2014). The benefits compared to PBCE, as discussed by Ward and Sobek (2014), Endris et al. (2012), Kennedy et al. (2014) and process comparison shown in fig. 5.11, are the following:

- Reduce the amount of rework due to elimination of late iteration loops
- Reduce costly late changes due to elimination of early decisions based on assumptions
- More robust solutions due to delayed design choices based on real data and optimisation
- Reduce unpredictability of downstream activities due to minimising planning based on "unknown"
- Prioritise eliminating weaker options instead of finding one best alternative
- Minimised risk for detailed development as feasibility is tested early and more accurate data is available by the time of design decisions
- Emphasise manufacturing as one of the stakeholder of design development
- Increased knowledge creation and reuse, visibility of knowledge gaps
- Encourage knowledge visualisation and sharing in a structured manner

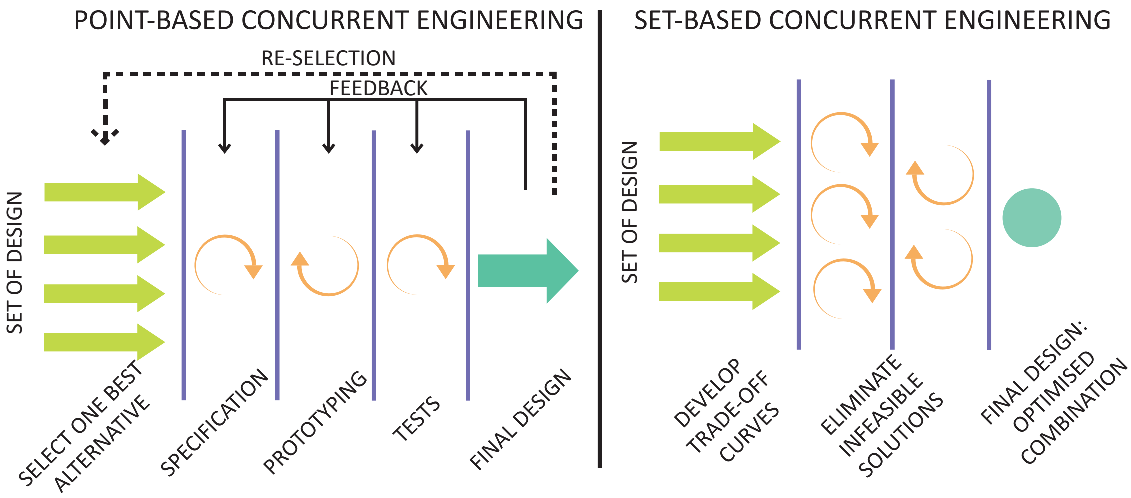

Figure 5.11: PBCE vs SBCE model (Sobek et al., 1999)

The implementation of SBCE as a development model is the final stage of LPPD establishment on the organisational level as it comprehends the overall mindset of "lean thinking" and makes use of the previously introduced tools. Thus, it is the final outcome of developing a lean development organisation and does not show effect on its own but has a compound effect of the building blocks of the framework and other "lean enablers" (Tortorella et al., 2015).

Researchers have developed further approaches to how to manage the creation of design sets and multiple alternatives. For instance, Augustine et al. (2010) introduce hybrid concept creation and discuss elimination principles of concept evaluation. The approach on developing evaluation criteria is adapted to individual sub-system evaluation which goes in line with assessing sets. Also, a baseline is established by cost constraints – having a cost ceiling screening criteria – which is often crucial in development projects.

Furthermore, Endris et al. (2012) discuss the integration of simultaneous product and production development in the set-based environment. They propose evaluating manufacturing sets against lean manufacturing principles (i.e. waste categories) and emphasis the need of communication between the parties of alternatives considered in the sets for early integration.

SBCE ultimately seeks to eliminate the Stage-Gate® process which is widely implemented in larger companies to evaluate project progress and structure the development process. Ward and Sobek (2014) argue that the system opposes development flow by forcing to batch information and stop development work to prepare for gate reviews. Thus, it interrupts the natural flow and creates waste. SBCE framework proposes integration events to pull together current development efforts and review designs based on planned learning cycles. These are held more often and according to the tact of the scope of the project. However, SBCE and Stage-Gate® systems can be somewhat aligned as there is a spectrum between PBCE and SBCE where to position one's structure, showcased by successful case examples in Ward and Sobek (2014).

6

Countermeasures

The following chapter covers the countermeasure development phase – corresponding to the A3 flow. It starts with a new process flow build-up to determine the desired state. Next, the evaluation of suitable methods which were identified from the literature study and current organisational practices to mitigate the deficiencies are presented in section 4.2.

6.1 Concept Development

The development process was first mapped on the basis of the PDM group action and deliverables guideline according to the Philips Stage-Gate® and their own development principles. This showcased their current practices and tasks which are supposed to be completed and/or documented in some form. The flow-down was compiled in an Excel sheet. It involved a list of actions and milestone deliverables with references to available templates and instructions in the engineering group's SharePoint site. The standard forms and the guideline itself were in a draft stage as this initiation had not been completed yet to unify the practices across development projects. Thus, most of the methods and approaches were quite raw and could be interpreted in various ways from different leaders as standardisation in ways of working was still low.

The concept development started off by crafting a desired state framework for the PDM group development process. It was compiled in a phase form to align it with the Philips Stage-Gate® system. Each phase was described by input actions, a central phase event of multiple tasks and output deliverables to better visualise the process, an example phase is shown in fig. 6.1. The build-up allowed to identify where there was a need for new methods and which actions or deliverables should be revised. As such, it was the basis for creating a value stream step-by-step and ease the transition.

The level of change for the development structure was between the extremes of

PBCE and SBCE as Philips had just rolled out the new Stage-Gate® system to align various development departments. As such, the idea was to accommodate as much "lean thinking" into the phase process as possible for a better organisational fit.

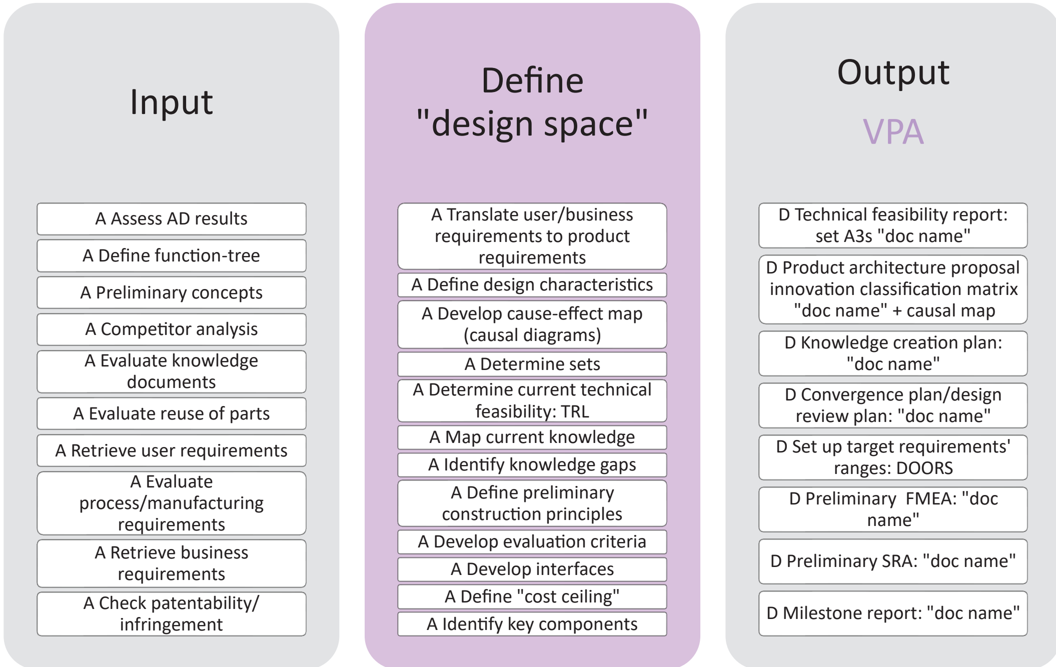

Figure 6.1: Actions and deliverables flow layout for one development phase

The first three stages, previously presented in fig. 3.1, were most resourceful for the PDM group, as it accommodates the greater part of the development work, and can benefit most from "lean enablers". As said, the process mapping combination set the development towards the SBCE model flow. Thus, the central events were determined as following:

- Define "design space"
- Convergence
- Detailed design
- Release for engineering build
- Release for pilot run
- Release components
- Release for delivery
- Project hand-over

From the literature review and current organisational practices 17 possible countermeasures as tools or approaches were identified. These could advance the development process with regards to the improvement areas identified in the root-cause analysis fig. 4.6. The countermeasures are presented in the table 6.1.

Table 6.1: Countermeasures

	Method	Description
1	Trade-off curves (section 5.2.1)	A visual form of documenting knowledge. Developing data based component interaction understanding by analysing system performance/financial trade-offs.
2	A3 reports, (section 5.2.2)	Standard reporting template. Guide for communicating design task or improvement action outcomes through customised templates for knowledge gaps, set designs, design reviews, root-cause analysis and improvement initiatives.
3	Checklist (section 5.2.3)	Design guideline and knowledge capturing form for component development. Guideline describes the design task process with inputs from process flow actions/deliverables and design pitfalls from FMEA analysis. Knowledge is captured during the development as a list of notions for future design consideration and referral to relevant knowledge documents. Also, a support for a design review preparation.
4	Innovation classification diagram (section 5.2.4)	Scoping project innovation through a visual representation of system improvements. Addressing a scale of novelty for system components and possible assessment of resource effort.
5	Causal maps (section 5.3.1)	A form of visualising system component interactions and relationships. Analysing change effect, requirement traceability and trade-offs.
6	Quality function deployment + TRIZ (section 5.3.2)	Detailed product definition through requirements flowdown and analysing trade-offs in a matrix form. Addressing translation of VOC to product requirements and innovation through resolving identified compromises.
7	Advanced FMEA (section 5.3.3)	Revised traditional FMEA with emphasis on failure prevention and part–function association. Added analysis of the design process risks to address possible pitfalls of the development with the specific project circumstances. Added design error tracking for documenting unexpected failures during development and post launch.

8	Narrowing matrix (evaluation)	In order to help the mind-set transition from traditional Pugh evaluation, which involves evaluating different concepts based on assumptions if they perform better or worse than the "datum concept" and choosing the winning alternative (Ullman, 2010), an advancement would be to address real data. The matrix could aid concept disregarding if found not to be in feasible bounds (design space) or combine set alternatives for evaluation to find the most optimal product system.
9	Error database (section 5.3.3)	Gather project based error tracking data from FMEA to analyse development process inefficiencies or improvement action effects. Identify areas which need revision.
10	Value stream mapping (section 5.4.1)	Process layout form to reach a new desired state of the development structure. Step-by-step analysis of the process flow to eliminate waste and align development tasks for increased value creation.
11	Design structure matrix (section 5.4.1)	Align concurrent engineering efforts with a project planning matrix. Identify a sequence of activities which results in shortest development time.
12	Standard skill-set (section 5.4.2)	Develop a toolbox with standardised templates and/or guides for design task execution. Establish the use across development projects and give baseline training for all engineers.
13	Mentor/coach (section 5.4.2)	Leadership through teaching subordinates for independent actions and taking responsibility. Communicate standard ways of working and support carrying out design tasks.
14	Chief engineer (section 5.4.2)	A project manager with technical knowledge of the product systems who create and lead the development through realising their vision based on studying the customer. Addressing customer value translation to technical requirements.
15	LAMDA (section 5.4.3)	Improvement cycle: look-ask-model-discuss-act. An advancement of PDCA to enhance communication and sustainable improvement actions.

16	SBCE (section 5.4.4)	Lean development model with concurrent design of sets for increased exploration of alternatives and delayed decisions for finding an optimal concept when the knowledge for decision-making is acquired.
17	Kamishibai boards	Lean production action tracking system. Visualising project or improvement action progress through showcasing the completion of action cards. Assigning phase activities or deliverables and facilitate quick analysis of the project status (Mascitelli, 2011).

Some of the methods were already established to some extent or in a varying form in the BG Coffee or other Philips development departments. In the PDM group a base template for the FMEA and a digital PDCA version to track tasks in progress were in use. Also, some projects had A3 report templates for communication. Furthermore, in other areas some set-based thinking principles were established and DSM was used for lean scheduling (Radeka, 2013).

6.2 Concept Evaluation

The 17 countermeasures were assessed based on their relation to improvement areas presented in section 4.2 and level of solution and robustness described in section 2.2.3. The final evaluation was a four-level assessment of the combined effect in the three categories. Also, the current practices and literature review information on the benefits and drawbacks of each tool was taken into account. The used symbols are explained in fig. 6.2. The evaluation of the countermeasures is presented in fig. 6.3.

Figure 6.2: Countermeasure final assessment legend (Shook, 2009)

For example, the method "trade-off curves" corresponded to five improvement area directions within the DERC field of "knowledge", "organisation" and "communication". The tool supports easy knowledge capture and sharing. Also, it encourages to gather more data for better understanding of the system and make fact-based decisions. The solution level is "level 2: process" as it improves the knowledge management process individually and robustness level is "level 5: prevention" as TOCs should minimise the risk of erring actions. The final assessment of the method was "outstanding" as TOCs improve many areas of processes across development actions.

	Tool/approach	Improvement areas	Solution	Robustness	Evaluation
1	Trade-off curves	Increase understanding of functional relations and visibility of knowledge gaps and/or use Develop "decisions based on facts" mentality Develop a sustainable "knowledge flow" framework Develop sustainable communication flow Develop documentation principles	Level 2: process	Level 5: prevention	●
2	A3 reports	Standardised design review process Develop "retrospect" framework Develop a sustainable "knowledge flow" framework Develop sustainable communication flow Develop documentation principles Build toolbox synergy to advance development traceability	Level 2: process	Level 3: inspection	●
3	Checklist	Standardised design review process Develop a sustainable "knowledge flow" framework Develop "new employees" training framework Develop sustainable communication flow Develop documentation principles	Level 2: process	Level 4: detection	●
4	Innovation classification diagram	Introduce further visualisation tools for action tracking Develop sustainable communication flow Re-evaluate portfolio management	Level 2: process	Level 2: improvement	○
5	Causal maps	Increase understanding of functional relations and visibility of knowledge gaps and/or use Develop sustainable communication flow Develop documentation principles	Level 2: process	Level 2: improvement	●
6	Quality function deployment + TRIZ	Increase understanding of functional relations and visibility of knowledge gaps and/or use Develop sustainable communication flow Develop documentation principles	Level 2: process	Level 1: tool	△
7	Advanced FMEA	Increase understanding of functional relations and visibility of knowledge gaps and/or use Build toolbox synergy to advance development traceability	Level 2: process	Level 5: prevention	○
8	Narrowing matrix	Develop "decisions based on facts" mentality Standardised design review process Build toolbox synergy to advance development traceability	Level 2: process	Level 3: inspection	○

9	Error database	Introduce further visualisation tools for action tracking Develop "retrospect" framework Re-evaluate portfolio management	Level 1: problem	N/A	○
10	Value stream mapping	Introduce further visualisation tools for action tracking Advance supplier knowledge feedback loop Develop sustainable communication flow Build toolbox synergy to advance development traceability	Level 3: system	Level 2: improvement	●
11	Design structure matrix	Introduce further visualisation tools for action tracking Increase understanding of functional relations and visibility of knowledge gaps and/or use Develop sustainable communication flow Re-evaluate portfolio management	Level 2: process	Level 2: improvement	●
12	Standard skill-set	Standardised design review process Develop a sustainable "knowledge flow" framework Develop "new employees" training framework Develop sustainable communication flow Develop documentation principles	Level 3: system	Level 1: tool	●
13	Mentor/coach	Build toolbox synergy to advance development traceability Develop a sustainable "knowledge flow" framework Develop "new employees" training framework Develop sustainable communication flow	Level 3: system	Level 2: improvement	●
14	Chief engineer	Re-evaluate portfolio management	Level 3: system	Level 2: improvement	△
15	LAMDA	Develop "decisions based on facts" mentality Develop "retrospect" framework Develop "new employees" training framework	Level 3: system	Level 5: prevention	●
16	SBCE	Develop "decisions based on facts" mentality Standardised design review process Develop a sustainable "knowledge flow" framework Advance supplier knowledge feedback loop Build toolbox synergy to advance development traceability Re-evaluate portfolio management	Level 3: system	Level 5: prevention	●
16	Kamishibai boards	Introduce further visualisation tools for action tracking Develop sustainable communication flow Re-evaluate portfolio management	Level 2: process	Level 2: improvement	○

Figure 6.3: Countermeasure evaluation *(colour-coded)*

The assessment was quite abstract given that the evaluation criteria was mainly determined based on the researcher's assumptions with the knowledge of the BG Coffee organisational framework and literature review as well as feedback from employees. Thus, the final combination of suitable methods was decided by their co-effect, fit for the BG Coffee organisational environment and contribution to reaching the desired state.

The evaluation resulted in ten methods assessed as “outstanding”, five “ good” and two “possibly adequate”. The tools in the first category were proposed for further validation with the test group. The methods from both categories, “outstanding” and “good”, were considered for implementation to reach the desired state towards the SBCE development model.

6.2.1 User Group Testing

A platform development project with set-based design thinking was initiated by the company supervisor which allowed to test out some of the methods with a user group of four engineers and involve other technical experts for reviews/integration events. The project was in early stages and most fruitful tools for initial development and communication were put into practise. These were the following:

- Trade-off curves
- A3 reports
- Causal maps

The main aim was to evaluate the response to set-based thinking and the benefit of the mentioned tools. As such, short interviews were held with three engineers who were available to discuss their opinions about the approach. The guideline for the interview is shown in appendix B.

The overall impression of structuring the development process with set-based design and using the above mentioned methods was well received. The main benefits mentioned were the following:

1. Clear communication – using structured methods to focus on critical areas of discussion and document development process as well as the outcome
2. Knowledge capturing – documenting knowledge during task execution as a way of working, standard templates for sharing learnings
3. Visualisation – easy transfer and clear overview of acquired data
4. Visibility of knowledge gaps – addressing function/component/requirement relation effects and trade-offs which trigger new trails of thought and understanding of needed knowledge
5. Identifying critical interactions – determining most relevant characteristics and trade-offs in development through combining data sets

All the interviewees would recommend these practices for other projects. Regarding set-based design, the user group saw an opportunity in aligning advanced and industrialisation development activities with the SBCE framework. It could ease the transfer of projects and especially knowledge to minimise rework and define expectations of input/output from both sides. Some raised the question of the suitability of SBCE for every project and felt a lack of understanding about the whole process with new methods rushed into the project without proper training. Other concerns related to the introduced tools were:

1. Losing sight of the system – focusing on individual sets exploration and generating out-of-scope learnings
2. “Missing a box” – standardised forms may create a false sense of security, if all the boxes are ticked but a necessary box is missing altogether
3. Stored on the shelf – all the generated reports are missing a database which could lead to losing the gathered knowledge again

Furthermore, some group members thought that the new approach had surfaced a lot of additional work to put all the knowledge “on the table” as no knowledge management was previously in place. As such, it could distort the effect of the trial run and seem very resourceful. In addition, there were opinions that the process development is taking over the technical development which could hurt the success of the project and reflect negatively on the SBCE approach.

More information was gathered through attending project meetings and integration events to observe the outcome of established methods. As the SBCE involves a mind-set change for engineers coming from a point-based development system and lack of practices addressing knowledge management, there were multiple lessons during these activities where and what to focus on while conducting the change. The observed attention points were:

1. Enforcing learning cycles – difficulty focusing on learning during exploration phase as engineers fall back onto providing single solutions
2. Clear project innovation scope – identifying multiple knowledge gaps may easily lead the sets out-of-bounds of the project as many interrelations go further from the selected innovation areas and ease prioritisation of set development and knowledge gap closure
3. Finding relevant trade-offs – combining data sets in order to gain insight of actual trade-offs and identifying “tipping points” which takes time and practice
4. Preparation for meetings – reviewing set maturity in team before integration events and sending information before-hand to attendees to focus meetings on decision-making
5. Importance of coaching – guiding engineers through the use of new methods with the principle of “learning by doing” and support transition with clear communication and expectations

6. Addressing determined design space – define target performance ranges to lead the discussion of feasibility and create baseline quality

Overall, the technical experts involved in integration meetings were also favourable of the way of working. Emphasising the importance of knowledge base, discussing technical learnings and sharing these. These inputs were considered for the implementation plan regarding future work for the BG Coffee development process improvement. Moreover, everyone acknowledge that implementing the SBCE framework itself is a learning process for finding the organisational fit and found the effort relevant for advancing the current state. The first two integration events already showcased growth and addressed previous lessons to improve the process “on the go”.

7

Implementation Plan

Given the gap between the current state of the development process for the PDM group and the desired state, a roll-out plan was compiled for future guidance. It involves 11 steps to develop towards set-based design thinking. As most of the tools identified in chapter 6 were "lean enablers", it was deemed reasonable to first establish individual approaches supporting the SBCE model which would eventually pull the set-based design to reach the desired framework.

The sequence of steps, presented in table 7.1, were determined based on the ease of establishment – already available base templates/known practices – and effectiveness – tools which correspond to multiple improvement areas. In addition, the lessons from user group testing were taken into account. Furthermore, the combined effect of certain approaches was considered to benefit the transition. For example, causal maps work well together with TOCs which form the base for lean knowledge management. These methods pull for standardised documentation which paves the way for the establishment of A3 reports.

Table 7.1: Implementation plan

Step	**Action**	**Method**
1	Introduce "lean thinking" ideas to technical leads	LPPD framework (SBCE) + coaching/mentoring + standard skill-set
2	Revise phase actions and deliverables: validate desired state	Modified VSM
3	Introduce lean knowledge tools	Causal maps + TOC + A3 report
4	Standardise reporting	A3 reports
5	Advance/standardise current tools	Advanced FMEA + Narrowing matrix
6	Establish/standardise action tracking	Visualised planning tools + Lean scheduling

7	Establish overview of occurring design errors	Error tracking database
8	Improve project definition – visualise project scope and selective innovation	ICD
9	Establish part development traceability	Checklist
10	Re-evaluate and improve methods	Continuous improvement (LAMDA)
11	Develop set-based design thinking structure	SBCE

The integration of methods which assist the steps were further broken down into more detailed actions. Each of them involved either guidelines for set-up, for example a workshop layout, or tool description/development. Also, examples of usage and tips were added in the process. Altogether, nine tool implementation guides were developed based on suggestion from the literature and organisational knowledge. Three of these are described in following sections and others compiled in appendix D.

7.1 Trade-Off Curves Workshop

For introducing the trade-off curves to the engineers as a knowledge capturing method, an outline for a workshop was developed. It was based on the practices suggested in the literature by Ward and Sobek (2014) and Kennedy et al. (2014). The preparation and conducting the workshop is a six-step process shown in table 7.2. It is intended for the technical team leads for studying and applying the method themselves – "learning by doing".

Table 7.2: Trade-off curves workshop

Step	Action
1	Find a previously solved root-cause problem/prototype testing
	It has available testing data *Performance characteristics were investigated/Product requirement achievability was tested with varying part parameters* *Tested parameters were dependant (i.e. the change of one affects the other)/Tested parameters affected product function/realising the requirement*

2	Find a current problem from a development project
3	Arrange a meeting with technical leads
	One start-up meeting (1-2h) *Follow-up two weeks later (1h)*
4	Prepare start-up meeting
	Develop trade-off curves for examples (on the solved problems) *Have current problem scope data available*
5	Conduct the start-up meeting
	Introduce the current problem scope *Execute step 1 and 2 of "developing a trade-off curve" (another guideline)* *Showcase example trade-off curves with explanation on further development steps* *Assign data gathering for the current problem and draft trade-off curve development responsibility*
6	Conduct follow-up meeting
	Discuss the findings *Evaluate data validity* *Determine trade-off curve documentation (e.g. Knowledge Gap A3 report)*
7	Establish as a standard knowledge capturing practice in development

This is the starting point for integrating TOCs into development projects for efficient knowledge sharing and storing across the department. It will benefit communication and transferring learnings. The technical leads shall coach their sub-ordinates in a similar way to address relevant trade-offs for design decisions and exploring the design space further than just validating requirements.

7.2 Design Review A3 Report Creation

A3 reports were previously used in the organisation for root-cause analysis, decision-making and improvement actions in some projects. The design reviews were held sporadically and a draft guideline was found for peer reviews. To structure and standardise the events, an A3 report for a detailed design review was developed based on current template designs. The set designs were evaluated and iterated in a separate A3 construction.

The detailed design review focuses on the development storyline – current design status to desired performance with actions how to get there. The template encourages defining learnings and making decisions based on gathered data as well as provide an overview and checklist for baseline design task quality. It is shown in fig. 7.1.

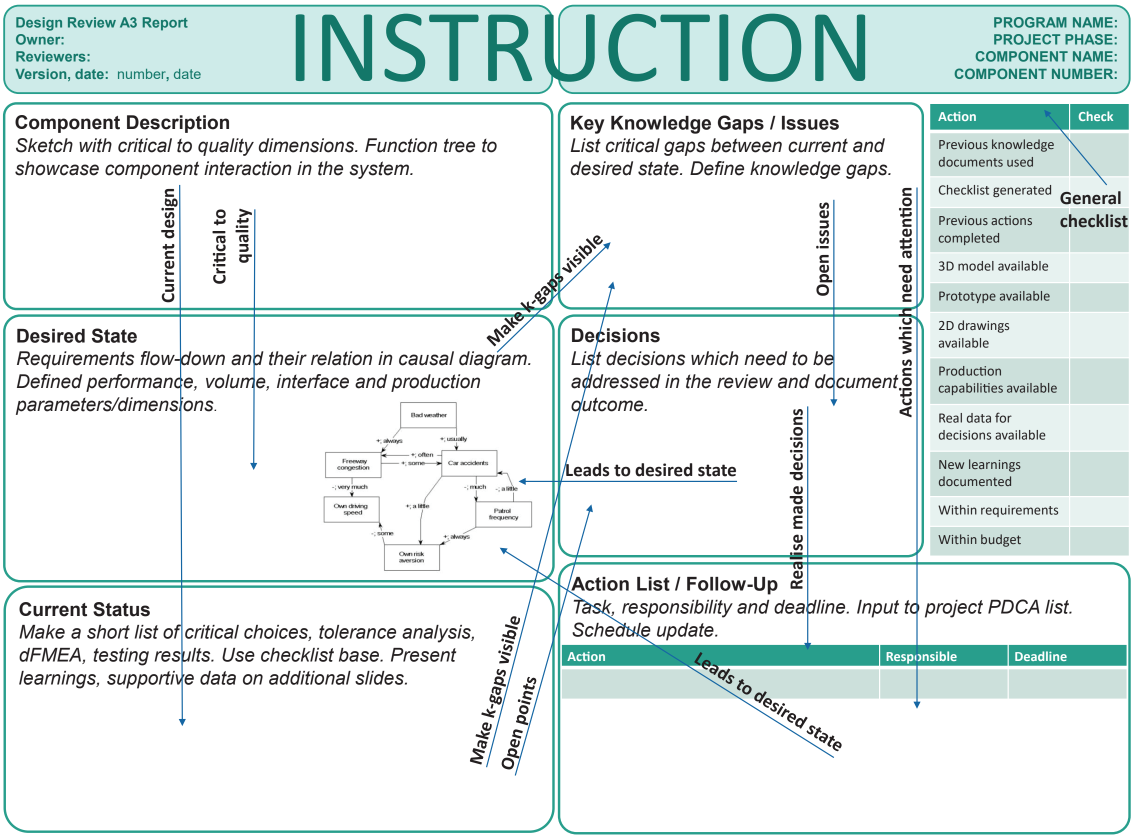

Figure 7.1: Detailed design review A3

For conducting an efficient review process, a guideline for a standard process was provided as presented in table 7.3. The A3 template aims to aid in focused evaluation of components and clear communication. In addition, it supports structured documentation and synergy between methods with links to the checklist/design process guide used to execute and capture the design task process knowledge.

Table 7.3: Design review process

Step	Action
1	Design review plan
	Establish a design review plan as a deliverable for first phase milestone *Tip: start off with first aligning the set design integration events and develop further for detailed design when optimised design system is chosen*
2	Set review
	Use the Set A3 for learning iteration and evaluation of alternatives *Along with the developed knowledge documents, the vase for detailed design*

3	Detailed design review preparation
	Use working design checklist and refined knowledge documents as base for creating the A3 *Use the review template to give clear information on design status* *Arrange a meeting with functional peers/other department engineers/technical experts* *Send the A3 (at least 3 days) in advance with filled boxes except the checklist and action list* *Let the invited know to study the A3 + additional data and come with questions and/or ideas for issue mitigation to effectivise the meeting*
4	Detailed design review (1-2h)
	Start off with a quick description and lead to questions *Facilitate the discussion towards decisions and necessary actions* *Determine action plan of further learnings, improvement ideas and design tasks*
5	Closure
	Transport action list to project group PDCA list *Update the A3 with review notes and outcome* *Send to attendees* *If necessary, propose a follow-up review meeting*

7.3 Advanced FMEA Template

As the FMEA was currently the central part for documenting project design development progress through addressing and mitigating failures and design errors, the template was further advanced with some additions. These involved features to generate reports for input to other tools in order to create synergy between different design process methods and enhance their outcome for quality product development.

Thus, the FMEA base template was adjusted to clarify tool usage, involve design process risks and generate checklists for part development or error reports. These are further described in table 7.4. The automatic report generation was executed with writing Excel macros for data withdrawal.

Table 7.4: Additions to the FMEA tool

Step	Action
1	Design process analysis

	Added column "task" (alongside "function" and "item") *Analyse design process risks regarding the six design error categories*
2	Distinction between "function" and "item"
	Relate each function to specific part/component to have both fields covered during analysis *To generate checklists based on "item"*
3	Design error tracking
	Documenting unexpected failures discovered during development or changes in previous log-ins (late additions) *Define error occurrence and classification for tracking* *Close loop by addressing root-cause analysis document and requirements' changes* *Generate error reports after project closure for overview and addressing inefficiencies*
4	Guiding questions
	Preparation guidance – questions regarding "function", "item" and "task" failures *Addressing noise factors and interactions between components*

The main goal of the additions is to advance traceability of decisions and documenting learnings as well as structuring error mitigation. Furthermore, the error tracking would give base data for addressing deficiencies in the development process and initiate improvement actions.

8

Discussion

Addressing product development process improvements resulted in transferring from a point-based development system towards set-based design thinking. It challenges the conventional practices to mature the organisational mind-set from product-stream orientation to knowledge-stream value creation in order to have a more sustainable long-term approach, as discussed in section 5.1. With the trends of implementing “lean practices”, the question that companies face is how to eliminate waste from all functional areas to increase quality output which would lead to short time-to-market, low cost and robust products.

As behavioural change needs inner motivation and is a steep learning curve, the process transformation takes a longer period of time. In order to arrive at the new desired state, incremental changes and step-by-step approach seems most fruitful for a larger organisation to reconstruct current practices and trails of thought. Thus, the most important aspect of sculpting a new development model is to have all employees on-board with the new adventure through showcasing waste and deficiencies in the current approach with relevant data. Alongside, the new tools and/or models should be presented with clear examples of their benefits and mitigation of identified inefficiencies. All the improvement actions and established methods will not have any effect, if they are not followed nor enforced by common practice.

Thus, like LPPD framework developers Ward and Sobek (2014), Kennedy et al. (2014) and others emphasise, the driving force in creating a change environment is strong leadership, coaching and “learning by doing”. In order to advance the innovation process regarding its efficiency, the management has to be aligned in values and principles which the organisation should strive for and relentlessly enforce the behavioural changes through mentoring their sub-ordinates.

As the main goal is to build a knowledge-based framework which needs establishment of knowledge management principles, there is no “quick-fix”. It will initially take more resources to capture currently available knowledge with new tools – trade-off curves, causal diagrams, checklists and structred documentation – which would benefit easy sharing and transferring lessons between projects. The effort is necessary for long-term goals of having a sustainable knowledge flow which would support successful product development project execution. Maintaining knowledge has proven to be troublesome for many organisations, as discussed in section 5.2, but is the key to excellence as in order to mature and grow, like any other individual, companies need to invest time in learning.

It is of course more challenging in smaller development teams and with limited resources which is the case for BG Coffee. This leads to the need of a clear project scope and selective innovation to focus learning cycles and exploration phases in SBCE towards well-defined goals. It involves inputs from other functional areas, like marketing and advanced development, to have a solid project initiation which would prevent scatter and waste of resources. The success of the project relies heavily on early phases of development, thus clear orientation will benefit choosing valuable learning cycles and decision-making with small resources. As such, the SBCE approach has to be understood and followed at all organisational levels to reap the benefits.

Regarding the implementation of SBCE for a variety of organisations in size and funding, the LPPD framework is mostly built upon behavioural changes not large monetary investments to have an effect. It provides more guidance through value prioritisation and principles rather than a strict structure to follow. Thus, it can be fitted to specific organisational needs and enables cultural modifications. For example, LPPD strives for eliminating the Stage-Gate® process but the lean tools can still be used in the named structure to advance the development process to a certain point. As previously stated, there is a spectrum between PBCE and SBCE and each organisation can choose the most beneficial position for their environment between the two according to their industry nature. Furthermore, the tools are intended for continuous improvement and easily modifiable which create a good balance between standardisation/structuring and creative freedom which is necessary for innovation.

As such, the future work which lies ahead for BG Coffee is finding the most suitable LPPD combination of the proposed methods for their development system to produce quality products on time and budget, starting with the alignment of shared values and organisational goals to strive for together as a team. Employees need to embrace experimenting and making mistakes to learn and grow towards a more sustainable development process.

9

Conclusion

Product development process improvements are multifaceted actions which involve changing organisational behaviour. In nowadays competitive and fast-changing markets, the research for finding efficient innovation practices is more and more turning into action research. Practitioners themselves are interested in studies to advance and challenge the conventional product development structures to deliver quality products on time and budget. This has led to extended studies on lean product and process development which is the new trend in product development process improvements. The thesis in hand was constructed to answer two related research questions to address advancements for the BG Coffee development process. The process was led by a problem-solving A3 approach – the final A3 can be found in appendix A.

RQ1. Why do design errors occur in the current Philips BG Coffee development department's way of working?

The first half of the study covered the analysis of current practices and the development process model inefficiencies to define improvement areas for BG Coffee. The findings amounted in design error root-causes "organisation", "communication" and "analysis" areas. As the underlining factor for the design task analysis is "knowledge", it was added under problematic areas as well – being the next contributor in the Pareto analysis. The results indicated a lack of standard practices applied across all projects for design communication and knowledge management in the development process. It contributed to poor analysis, rework, cost overruns and design errors. The major deficiencies – determined through in-depth interviews with a variety of developers and quality engineers – were the following:

- Lack of understanding in functional relations and visibility of knowledge gaps and/or use of knowledge
- Poor design review process
- Lack of learnings shared
- Missing knowledge management

- Absent design task execution guidance

RQ2. Which design process error-proofing methods and lean practices form a suitable base for improving the Philips BG Coffee development process?

The other part of the thesis addressed finding best practices through a literature study and organisational knowledge to develop countermeasures for closing the gap between current and desired state in BG Coffee. An LPPD framework was found most suitable as it focuses on building a knowledge stream and establishing effective communication principles for value-focused development. Thus, an implementation plan of "lean tools and approaches" was constructed to move towards set-based design thinking which is the core of lean product and process development. It involved the establishment of the following standard practices:

- Causal diagrams
- Trade-off curves
- A3 reports (Set A3, Knowledge Gap A3, Decision A3, Design Review A3, Root-Cause Analysis A3, Improvement Action A3)
- Advanced FMEA
- Planning visualisation boards and lean scheduling
- Innovation classification diagram
- Part development checklist

These were intended to streamline the development process for better tool synergy and increased emphasis on learning for knowledge creation which would be easily reusable. The set-up would eventually pull for the set-based design thinking model to reach the desired state in BG Coffee organisational setting.

The study in hand involved early trials of set-based design project establishment with the use of A3 reports, causal diagrams and trade-off curves. The process got favourable feedback from the engineers and surrounding technical groups of the development project. The major advancements were visibility of knowledge gaps along with well-defined learning cycles and increased exploration of system interactions/concept alternatives to find an optimal design.

9.1 Future Work

The future work in the BG Coffee comprises confirming the effect of the chosen methodology in pilot projects and a step-by-step plan execution. The results and lessons from the establishment process would benefit LPPD framework research with further validation and verification of the promised positive effects of the proposed methodology – a more predictable and sustainable product development system. It would also contribute to understanding the difference of implementing LPPD principles in an organisation with small project teams and carrying out the change with the current resources without full-time dedicated improvement leaders.

Furthermore, it would help closing the gap in research through providing practical information about the transformation from a PBCE to the SBCE model which is currently lacking in the field. Thus, it is highly recommended to monitor the long-term process of the implementation. The trial-error and a step-by-step plan execution approach is a great learning possibility for the organisation and other industries how to fit the LPPD framework to a specific organisational environment by addressing attention points and tips for crafting the roll-out process. The researcher encourages the BG Coffee development department to publish the results and lessons gathered during the process in the future as well as this thesis was just the starting point of the journey.

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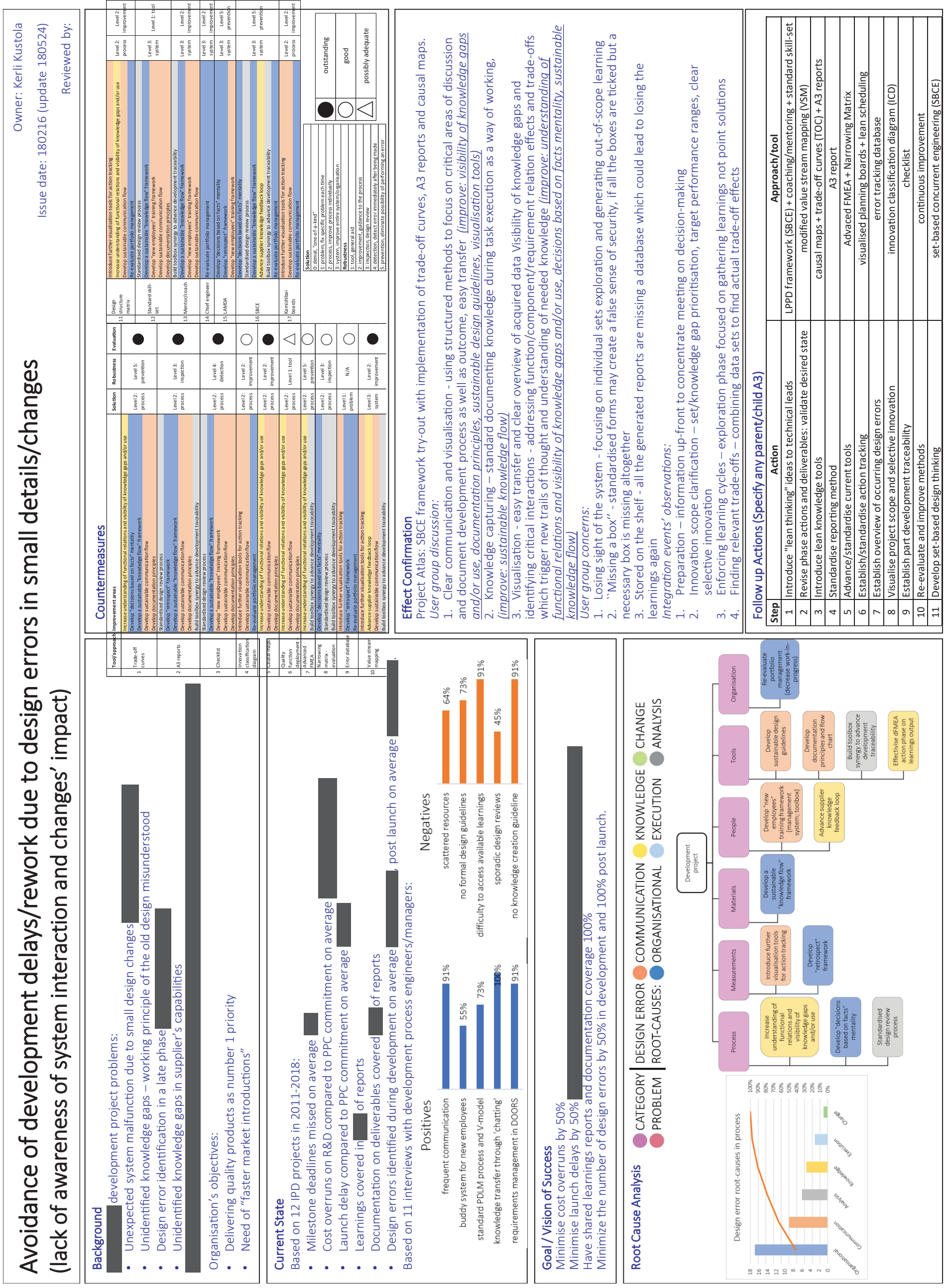
A

Thesis A3



Step	Action	Approach/tool
1	Introduce "lean thinking" ideas to technical leads	LPPD framework (SBCE) + coaching/mentoring + standard skill-set
2	Revise phase actions and deliverables: validate desired state	modified value stream mapping (VSM)
3	Introduce lean knowledge tools	causal maps + trade-off curves (TOC) + A3 reports
4	Standardise reporting method	A3 report
5	Advance/standardise current tools	Advanced FMEA + Narrowing Matrix
6	Establish/standardise action tracking	visualised planning boards + lean scheduling
7	Establish overview of occurring design errors	error tracking database
8	Visualise project scope and selective innovation	innovation classification diagram (ICD)
9	Establish part development traceability	checklist
10	Re-evaluate and improve methods	continuous improvement
11	Develop set-based design thinking	set-based concurrent engineering (SBCE)

B

Interview Guidelines

Interviewee

1. Name:
2. Position:
3. Mechanical engineering development experience:
4. In the coffee department:
5. Projects:

Part I

Mechanical engineering development process

1. Describe the phases
    a. Requirements
    b. Concept development
    c. Verification
2. Reviews
3. Working methods
    a. Structure
    b. Toolbox
    c. Knowledge use
    d. Problems/inefficiency
4. Improvement areas

Project under investigation

1. Involvement
2. Design process
3. Reviews
4. Problem identification
5. Rework

Part II

Product development toolbox/way of working

1. DOORS system – requirements management
    a. Traceability system – module – part
2. Planning for development
    a. Scheduling
    b. Action list
    c. Status
3. dFMEA process
    a. What is used for input?
    b. What are the guidelines?
    c. How is the output used in design execution?
4. Work in engineering teams
    a. How is the communication of design processed?
    b. How is the work allocated?
    c. Learnings
5. Documentation
    a. New SharePoint toolbox
    b. Responsibilities
    c. Traceability

User group interview guideline

Interviewee

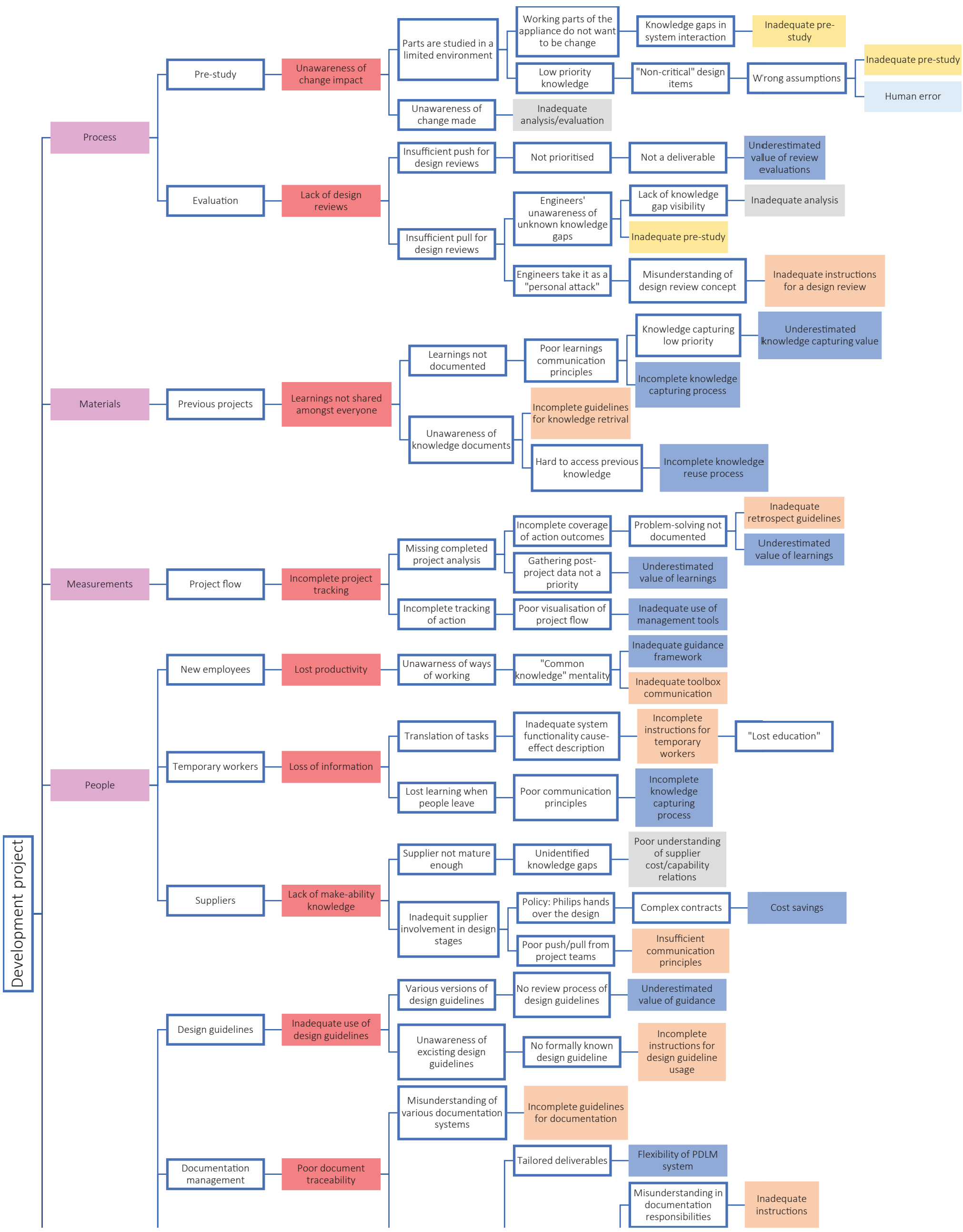
1. Name:
2. Position:
3. Mechanical engineering development experience:
4. In the coffee department:
5. Projects:

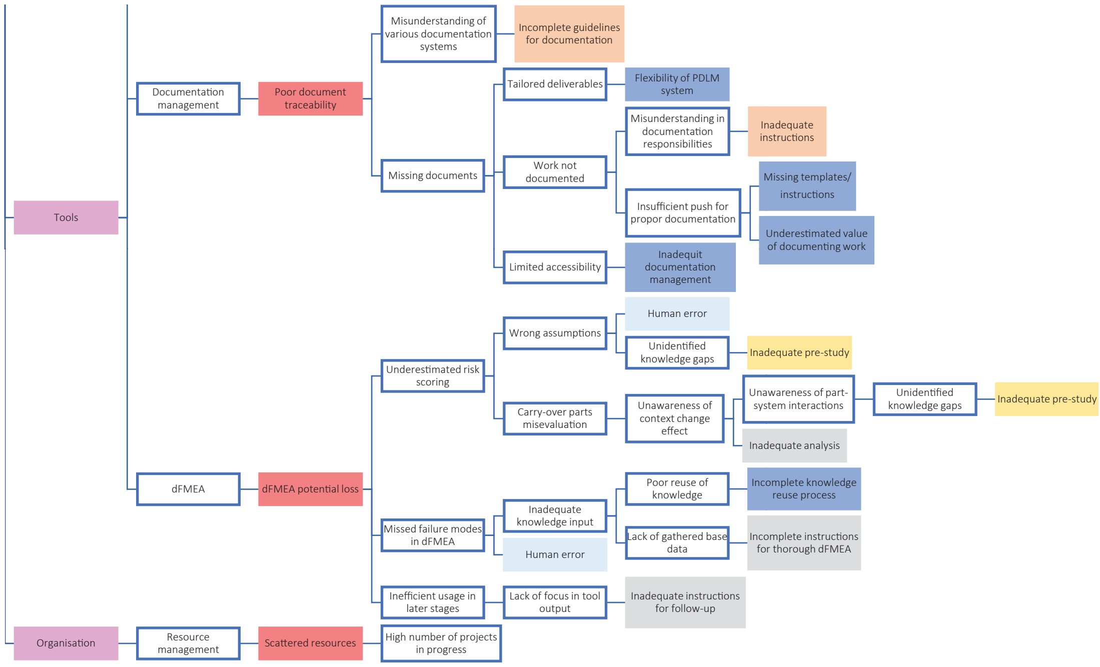
Set-based design project

1. Set-based process
    a. Described set-based design thinking
        i. Tools
        ii. Changes in ways of working
    b. Benefits
    c. Drawbacks
    d. Time resource
    e. Would you recommend it for other projects?
2. Trade-off curves
    a. User experience
    b. Benefits
    c. Drawbacks
    d. Would you recommend it to your co-workers?
3. A3 reports
    a. User experience
    b. Benefits
    c. Drawbacks
    d. What would you change?
    e. Would you recommend it to your co-workers?
4. Causal maps
    a. User experience
    b. Benefits
    c. Drawbacks
    d. Would you recommend it to your co-workers?

C

Root-Cause Analysis




Tools
Organisation
Documentation management
dFMEA
Resource management
Poor document traceability
dFMEA potential loss
Scattered resources
Misunderstanding of various documentation systems
Incomplete guidelines for documentation
Missing documents
Tailored deliverables
Flexibility of PDLM system
Work not documented
Misunderstanding in documentation responsibilities
Inadequate instructions
Insufficient push for propor documentation
Missing templates/ instructions
Underestimated value of documenting work
Limited accessibility
Inadequit documentation management
Underestimated risk scoring
Wrong assumptions
Human error
Unidentified knowledge gaps
Inadequate pre-study
Carry-over parts misevaluation
Unawareness of context change effect
Unawareness of part-system interactions
Unidentified knowledge gaps
Inadequate pre-study
Inadequate analysis
Missed failure modes in dFMEA
Inadequate knowledge input
Poor reuse of knowledge
Incomplete knowledge reuse process
Lack of gathered base data
Incomplete instructions for thorough dFMEA
Human error
Inefficient usage in later stages
Lack of focus in tool output
Inadequate instructions for follow-up
High number of projects in progress

D

Implementation Plan

D.1 Modified Value Stream Mapping and LAMDA

	Value creation workshop
1	**Analyse adherence to current process**
	Identify relevant flow-charts from company
	Analyse past projects and current practices in the department to determine deviations from the process map
	Analyse the availability and traceability of past documents and decision-making in projects
	Identify actual standard practices in use
2	**Arrange department leads meeting**
	Invite department leads
	Prepare analysis results
3	**Value creation analysis**
	Discuss deviations from the actions/deliverables list
	Determine current state of processes
	Discuss root-causes of deviated behaviour
	Validate standard practices across engineers
	Determine the value of current practices
	Identify improvement areas/wastes of current practices
	Align improvements with desired state with input/output events framework
	Assign LAMDA cycles

	Improvement cycle - LAMDA
1	**Root-cause analysis**
	Go through cycle phases Look-Ask-Model
	Compile findings in Improvement Action A3
2	**Discuss**
	Set up a meeting with involved department leads on the process
	Discuss findings of the improvement cycle and present countermeasure models
	Determine action plan
3	**Initiate improvement**
	Establish the improved model
	Monitor effects of the change
	Update Improvement Action A3
4	**Close cycle**
	Present improvement action results
	Identify and assign follow-ups

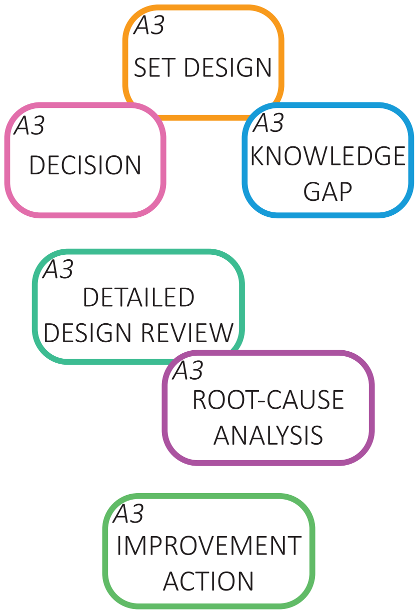
D.2 Causal Maps

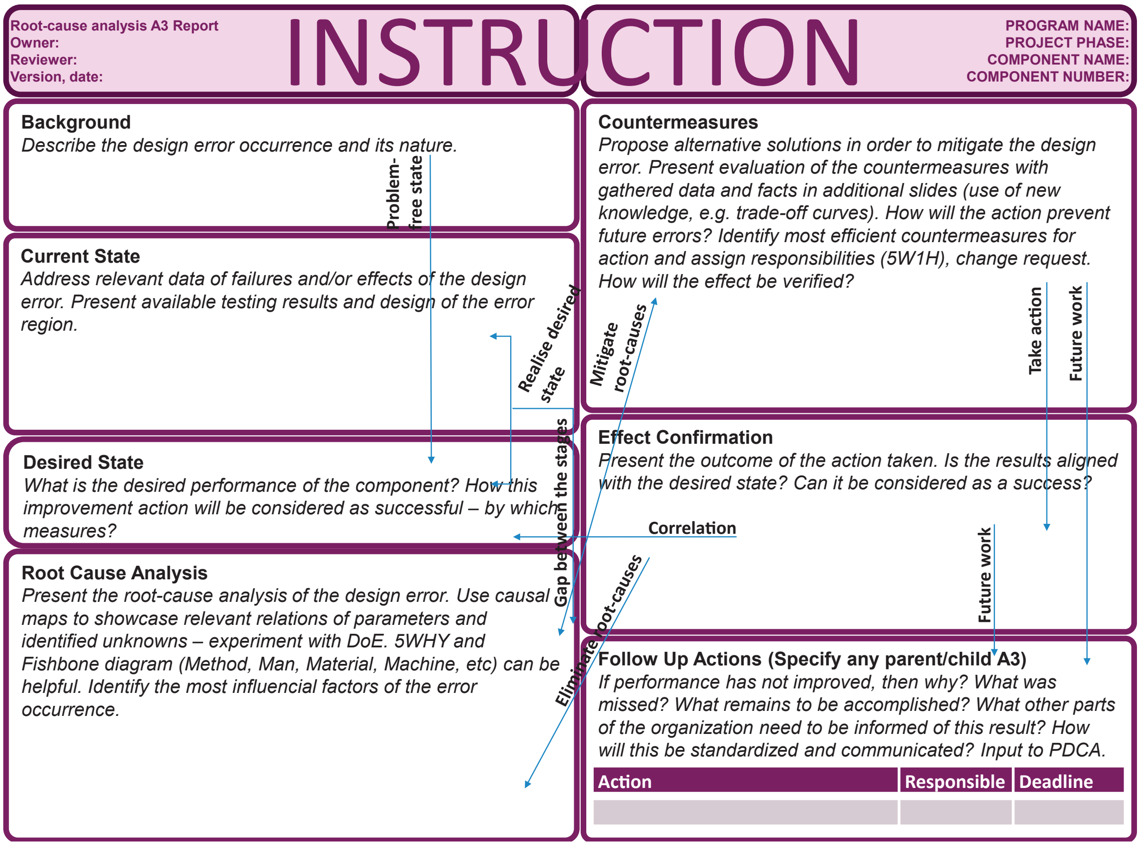
	Develop causal diagrams
1	**Define product system**
	Create function-relation structure of product architecture
	Identify relations and additional parameters affecting the functions
2	**Analyse the diagram**
	Determine relation effects (positive or negative)
	Determine critical to quality relations
	Identify knowledge gaps
3	**Identify sub-systems**
	Cluster independant systems
	Assign investigation areas and determine level of detail
4	**Develop causal diagram**
	Gather data/do test to determine the unknown relationships
	Advance causal diagram with developed knowledge
5	**Integrate to baseline knowledge documents**
6	**Refine over-time**

	Develop causal maps*
1	**Define layers**
	Determine purpose for causal map, e.g. change analysis, requirement traceability, causal diagram advancement
	Select necessary depth for relation investigation
2	**Develop causal map**
	Link layer components
	Evaluate relations
	Identify knowledge gaps
3	**Determine actions**
	Investigation areas
	Improvement areas
	Data driven decisions
*	Analysing change effect (e.g. developing new generation products)
	Good for requirement flow-down analysis
	Addressing root-cause problems

D.3 A3 Reports

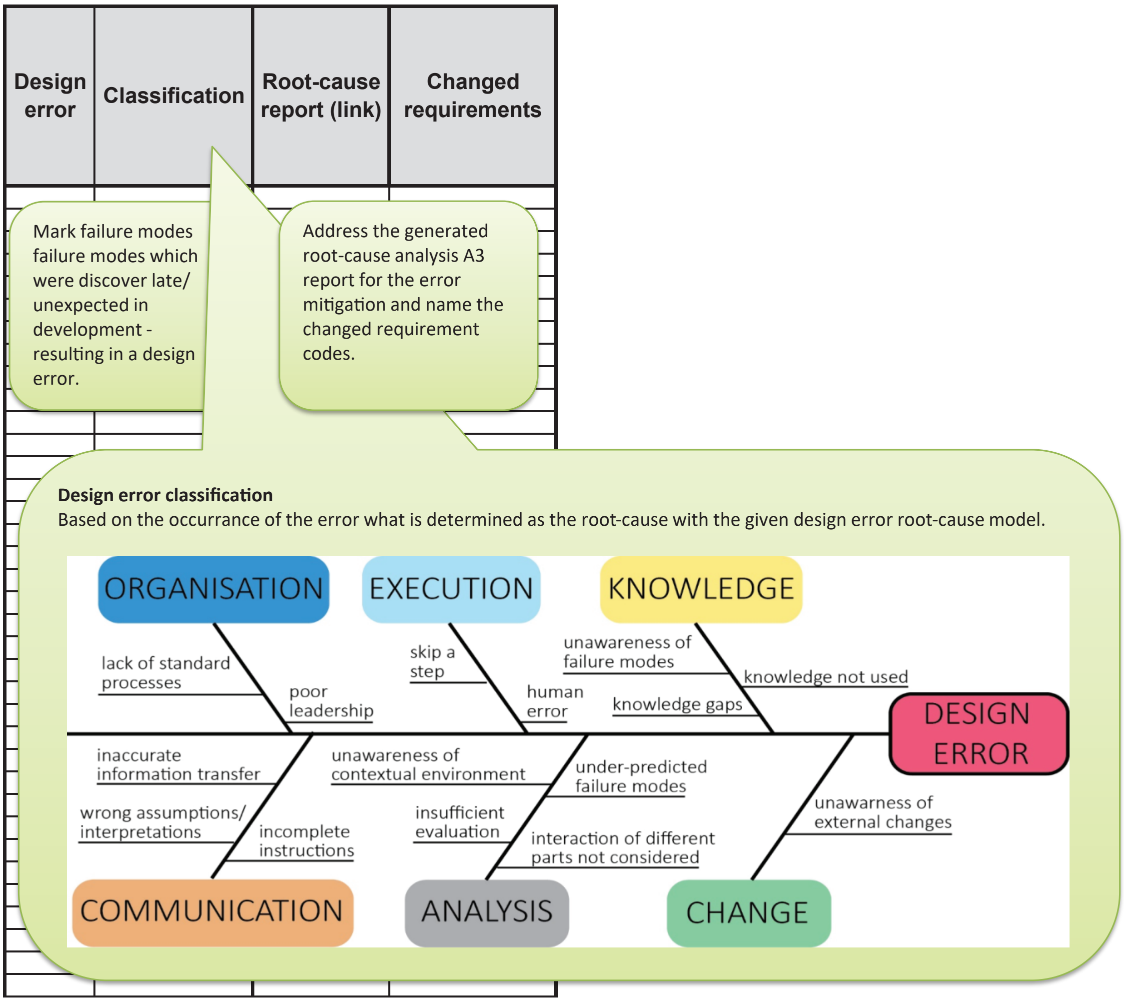
Standard A3 reports	
1	Set design A3 (linked)
	Set development process template
	Requirements - causal diagram - knowledge gaps - decisions
2	**Decision-making A3**
	Link to Set A3 decisions
	Factual data for design choice traceability
3	**Knowledge gap A3**
	Link to Set A3 knowledge gaps
	Guides learning cycles - TOCs development
4	Detailed design review (linked)
	Part development review - detailed design
	Component descripiton - current/desired state gap - decisions+actions for mitigating issues
5	Root-cause analysis (linked)
	Problem-solving action
	Design error mitigation
6	Improvement action (linked)
	Continuous process improvements
	Step-by-step road to SBCE





D.4 Advanced FMEA

Additions to FMEA template	
1	**Design process analysis**
	Added column "task"
	Analyse design process risks regarding the six design error categories
2	**Distiction between function and item**
	Relate each function to specific parts to have both fields covered during analysis
	To generate checklists based on items (components)
3	**Design error tracking**
	Documenting unexpected failures discovered during development (late additions)
	Define error occurence and classification for tracking
	Close loop by addressing root-cause analysis document and requirements change
	Generate error reports
4	**Guiding questions**
	Preparation guidance



D.5 Narrowing Matrix

Narrowing Matrix	
1	**Criteria development**
	Gather the CTQs, identified trade-off parameters and decisions from the set A3 development
	Address the requirement ranges for the evaluation (design space)
2	**Concept data**
	Gather REAL values for the proposed concepts given the criteria
	Base for later trade-off curve development and set evaluation
	Tip: use DOE practices, quick mock-ups and previously available testing data to define the values
	The values which are between the identified range turn green
3	**Evaluation - narrowing**
	Critically evaluate the given performance data of alternative concepts
	Determine which ones should be discarded (most of concept column cells not green)
	Draft trade-off curves on the given data and performance measures for knowledge documents - reference the location
	PS! The idea is NOT to choose the best alternative but to dismiss infeasible ones

No	Criteria	Notes	Reference document (link)	Lower limit	Upper limit	Unit	Concept 1	Concept 2	Concept 3
1	**Noise**			45	80	dBA	75	60	82
2	**Weight**				3	kg	2.4	2.1	2.8
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									

List the criteria found relevant in the set A3

Add any description / explanation to the criteria
What it takes into account

Reference the knowledge document where the data is stored

Requirement range (design space)
If there is a baseline which every concept needs to exceed or stay under - lower / upper limit

Gathered value for a specific concept performance measure
Green if within defined range - feasibility check

D.6 Checklist

Checklist establishment	
1	**Level**
	Suggested for detailed design to advance requirement traceability for part development and log tips for other designers which are too specific for knowledge document
2	**Establish ownership**
	Every designer takes care of his/her part development documentation, to log in the design decisions and process
	Updated with each new designer, previous log-ins as guidence and help for new employees
3	**Storing**
	The whole design guide should be arranged in folder along baseline knowledge documents for part specific knowledge
	The checklist should be attached to technical documentation for part review

Checklist development	
1	**Copy dFMEA generated checklist sheet to the document**
	Generate "item" checklist from dFMEA document (macro-app)
	Update it after each dFMEA update
2	**Develop design task input/output Ishikawa diagram**
	Update during execution
3	**Input relevant know-how gathered during the development**
	Requirements development traceability
	Design approach tips (tacit knowledge): DFA, DFM
	Testing and analysis suggestions
4	**Attach to part technical documentation**

Design guideline

Theme	Tip	Log-in	Owner	Knowledge document
Technical drawings	Add the step dimensions on the outer ring for clarity	11-05-18	Mark	X
DFA	Keep the horizontal side plate for easier alignment	11-05-18	Mark	"document link"
DFM				
Requirement choice				
Testing set-up				
Analysis set-up				
Other				

Choose the category for know-how knowledge

Write part specific knowledge acquired during design development

Log the time and ownership of input

Address the need of updating knowledge document
"X" if not necessary to add to baseline documents

Analysis set-up	tips for simulation, analysis tools
DFA	design choices made for easy assembly
DFM	design choices made according to manufacturing capabilities
Requirement choice	specific dimensions found suitable for *x* reason
Testing set-up	tips for testing practices
Technical drawings	crucial dimensions, attention points to add
Other	a tip outside the defined themes

"PART NAME" DEVELOPMENT "part number"

Input

Field	Input	Check
Knowledge documents	"document link"	YES
	"document link"	NO
	"document link"	
System requirements	"req. code"	
	"req. code"	
	"req. code"	
Set A3 reports	"document link"	
	"document link"	
	"document link"	
Construction principles	"design guideline"	
	"design guideline"	
	"design guideline"	
Linked tasks/ communication	other departments' input	
	production input	
	interfaced parts	
dFMEA	"document link"	

Main field of input to each design task

Specific documents / connections relevant for this part development
Developed and updated with each new owner, draft from set design

Checked during part development by the owner of the design task
Base for design review

Output

Field	Input	Check
Knowledge documents	"document link"	YES
	"document link"	NO
	"document link"	
Technical documentation	"document name"	
	"document name"	
	"document name"	
Deliverables	"document link"	
	"document link"	
	"document link"	
Linked tasks/ communication	input to other departments	
	input to production	
	interfaced parts	

D.7 Innovation Classification Diagram

	Develop innovation classification diagram
1	**Determine classification**
	Derive project scope definitions
	Derive past innovation examples
	Define low-medium-high-novel innovation criteria and responsibility for the innovation (e.g. expected from AD projects or PDLM)
	Colour-code innovation classification
2	**Develop innovation classification model**
	Choose a product system
	Derive product architecture sketch
	Apply classification on previous project examples
	Establish use in project initiation for determining project scope
3	**Develop resource allocation predictability**
	Analyse previous project information on classification levels
	Identify average resource/development time for each level
4	**Use data in portfolio management**

D.8 Set-Based Concurrent Engineering

	Set-based concurrent engineering system development set-up
1	**Develop target range system criteria**
	Translate customer and business requirements to target design requirements (given in range)
	Determine manufacturing capabilities
	Develop product system causal diagram - holistic overview
	Define innovation scope (innovation classification matrix)
2	**Determine design sets**
	Use the causal diagram to identify sub-systems
	Create project plan outline (set development and convergance events)
3	**Determine design space**
	Retrieve relevant requirements' ranges
	Develop set causal diagram
	Evaluate knowledge documents, AD results and current sub-system concepts
	Determine criteria for concept evaluation
	Refine requirement ranges based on currently available data
	Identify knowledge gaps
	Report findings in the Set A3 Report
	Refine project plan according to set maturity
4	**Exploration phase**
	Gather data for knowledge gaps
	Test concepts to performance limits
	Develop trade-off curves
	Report findings in the Knowledge Gap A3 Report
5	**Set review event I (team)**
	Discuss trade-off curves
	Evaluate concepts on criteria and given data
	Eliminate infeasible concepts

	Eliminate infeasible concepts
	Develop hybrids/new concept direction based on new knowledge
	Refine criteria and requirement ranges
	Identify additional knowledge gaps
	Report findings in the Set A3 Report update
6	**Preparation for convergance/integration**
	Gather data for additional knowledge gaps
	Refine concepts
	Send reviewed set A3 in advance of the event for study
	Experts should prepare questions, critical feedback for the event
7	**Convergence/integration event I (team + technical experts)**
	attendees
	Determine set out decisions and identified exploration areas
	Update A3 with meeting notes and send to attendees
8	**Optimisation**
	Gather data for additional knowledge gaps
	Refine concepts
9	**Set review event II (team)**
	Evaluate concepts on criteria and given data
	Eliminate infeasible concepts
	Narrow down to few alternatives for system convergance
	Report findings in the Set A3 Report update
	Send reviewed set A3 in advance of the event for study
10	**Convergence/integration event I (team + technical experts)**
	Discuss any questions for each set
	Combine sets in different ways
	Evaluate on system criteria based on data
	Eliminate infeasible concepts
	Converge on an optimal design based on data
	Finalise product requirements
	Report findings in the Set A3 Report update
11	**Plan detailed design**