

**POLITECNICO DI MILANO**

**Department of Management, Economics and Industrial Engineering**



Ph.D. in Management, Economics and Industrial Engineering

**SET BASED CONCURRENT ENGINEERING (SBCE)**

*A learning method to increase awareness level in industry*

&

*A methodology to identify and prioritize areas at a product level*

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- XXV Cycle –

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## **Declaration**

I hereby declare that I am the sole author of this Ph.D. thesis and assure that no other resources than those indicated have been used in the accomplishment of this work. Sources that have been used or adopted from other works (both published and unpublished) are cited based on the information obtained as dated.

*June 2013, Kerga Endris*

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# CONTENTS

<b>Lists of Figures</b> .....	<b>VI</b>
<b>List of Tables</b> .....	<b>VIII</b>
<b>1 SYNTHESIS</b> .....	<b>1</b>
1.1 Thesis structure .....	2
1.2 Research background .....	4
1.2.1 PART I – A learning method to increase awareness level of SBCE in industry .....	5
1.2.2 PART II – Methodology for identifying and prioritizing areas to apply SBCE.....	15
<b>2 INTRODUCTION TO PRODUCT DEVELOPMENT</b> .....	<b>4</b>
2.1 Introduction.....	5
2.2 Problem solving approaches in product development .....	6
2.2.1 Design – build – test approach .....	7
2.2.2 Test – build – design approach.....	8
2.3 Point Based Serial Engineering (PBSE).....	9
2.4 Point Based Concurrent Engineering (PBCE).....	11
2.5 Limits and risks of PBCE.....	14
2.6 Set Based Concurrent Engineering (SBCE) in brief.....	15
2.7 Conclusions.....	17
<b>3 SET BASED CONCURRENT ENGINEERING IN CONTEXT</b> .....	<b>20</b>
3.1 Introduction.....	21
3.1.1 SBCE definition and principles .....	21
3.1.2 Principle of exploration .....	23
3.1.3 Principle of set based communication .....	24
3.1.4 Principle of convergence .....	25
3.2 Comparison of SBCE with similar approaches .....	27
3.3 Conclusions.....	29
<b>4 ENABLERS OF SET BASED CONCURRENT ENGINEERING</b> .....	<b>32</b>
4.1 Introduction.....	33
4.2 Customer value research .....	34
4.2.1 Customer value capturing.....	35
4.2.2 Integrating customer value .....	37
4.3 People competence.....	39

4.4	Process practices .....	41
4.4.1	Organization .....	41
4.4.2	Involvement.....	43
4.4.3	Integration .....	44
4.5	Intra/ inter knowledge transfer .....	47
4.5.1	Intra knowledge identification, capturing and documentation .....	47
4.5.2	Inter knowledge transfer and use .....	47
4.6	Tools/ methods/ technologies adoption .....	49
4.6.1	Capturing and integrating customer value .....	49
4.6.2	Exploration of alternative sets .....	51
4.6.3	Communication of alternative sets .....	56
4.6.4	Convergence of alternative sets .....	59
4.7	Conclusions.....	61
<b>5</b>	<b>RESEARCH GAPS, OBJECTIVES OF THE THESIS AND RESEARCH METHODOLOGIES FOLLOWED.....</b>	<b>63</b>
5.1	Introduction.....	64
5.2	Research gap one – Low awareness level of SBCE in industries .....	65
5.2.1	Awareness gap and the growing interests in industries.....	65
5.2.2	Field study on awareness gap .....	66
5.2.2.1	SBCE adoption and effectiveness.....	68
5.2.2.2	Design knowledge capturing and reusing .....	69
5.2.3	Research objective and methodologies followed.....	71
5.3	Research gap two – Lack for a systematic methodology for identifying and prioritizing areas to apply SBCE.....	73
5.3.1	Research objective and methodologies followed.....	74
5.4	Conclusions.....	76
<b>PART I.....</b>		<b>78</b>
<b>6</b>	<b>A LEARNING METHOD TO INCREASE AWARENESS LEVEL OF SBCE IN INDUSTRY... 78</b>	
6.1	Introduction.....	79
6.1.1	State of the art of serious gaming .....	79
6.1.2	Existing serious games in concurrent engineering.....	81
6.2	Introduction to SBCE serious game .....	84
6.2.1	Framework of SBCE serious game.....	84
6.2.2	Inputs to SBCE serious game .....	85

6.2.3	Stage-one of SBCE serious game .....	87
6.2.4	Testing in stage-one of SBCE serious game.....	88
6.2.5	Performance measurement of players in SBCE serious game .....	89
6.2.6	Stage-two of SBCE serious game.....	91
6.2.6.1	Step A: exploration of alternative subsystems solutions.....	92
6.2.6.2	Step B: elimination of incompatible subsystems solutions .....	94
6.2.6.3	Step C: elimination of infeasible system solutions .....	95
6.2.6.4	Step D: selection of an optimal system.....	96
6.2.6.5	Measuring the learning outcomes in SBCE serious game .....	97
6.3	Validation of SBCE serious game in industry .....	98
6.3.1	Declarative learning outcomes .....	99
6.3.1.1	Set based communication and its practicality .....	100
6.3.1.2	Designers vs. Managers in SBCE.....	101
6.3.1.3	People experience and SBCE .....	102
6.3.2	Procedural learning outcomes .....	103
6.3.2.1	Perceived performance benefits of SBCE.....	105
6.3.2.2	Innovation and SBCE.....	105
6.3.2.3	Perceptions of SBCE benefits: Designers vs. Managers .....	107
6.3.3	Strategic learning outcomes .....	107
6.3.3.1	Problem solving and SBCE.....	108
6.3.3.2	Challenge in generating tradeoff and limit Curves .....	109
6.3.3.3	Interests to adopt SBCE: Designers vs. Managers.....	110
6.3.3.4	Competence development in SBCE.....	110
6.3.4	Summary of implications for practice .....	111
6.3.4.1	Definitions of summated scales .....	111
6.3.4.2	SBCE enablers, performance improvements and implementation success .....	114
6.4	Conclusions, limitations and future researches.....	118
<b>PART II.....</b>		<b>124</b>
<b>7</b>	<b>METHODOLOGY FOR IDENTIFYING AND PRIORITIZING AREAS TO APPLY SBCE ..</b>	<b>124</b>
7.1	Introduction.....	125
7.1.1	Contradictions, trade-offs and SBCE .....	125
7.1.2	Criteria and assumptions considered .....	127
7.2	Introduction to SBCE Innovation Roadmap (SBCE IR) .....	129

7.2.1	Identify customer requirements and assign importance .....	130
7.2.2	Assess competitors' products and set targets .....	134
7.2.3	Identify system contradictions .....	135
7.2.4	Identify causal contradictions .....	135
7.2.5	Derive rules to prioritize contradictions .....	138
7.2.6	Map contradictions to design factors .....	140
7.3	Validation of SBCE IR methodology .....	140
7.3.1	Case study on Adiabatic Humidification System (AHS) .....	140
7.3.1.1	Identify customer requirements and assign importance .....	142
7.3.1.2	Assess competitors' products and set targets .....	145
7.3.1.3	Identify system contradictions .....	145
7.3.1.4	Identify casual contradictions .....	146
7.3.1.5	Derive rules to select contradictions to start SBCE processes .....	150
7.3.1.6	Map contradictions to design factors .....	152
7.3.1.7	Plan for SBCE to overcome contradictions .....	153
7.3.2	SBCE on Rack subsystem .....	154
7.3.2.1	Basics of Rack subsystem and mapping T21 to design factors .....	155
7.3.2.2	Exploration of Rack concepts for non-VDI market .....	156
7.3.2.3	Testing Rack concepts .....	158
7.3.2.4	Merging Rack concepts .....	160
7.3.3	Assessment of SBCE IR by AHS experts .....	160
7.3.3.1	Differences and synergies with existing methods used in the company .....	161
7.3.3.2	Effectiveness of SBCE IR .....	163
7.3.3.3	Simplicity/ difficulties/ scalability/skills and capabilities needed to build and use SBCE IR	165
7.4	Conclusions, limitations and future researches .....	168
<b>8</b>	<b>THESIS SUMMARY AND FINAL CONCLUSIONS.....</b>	<b>172</b>
8.1	Integrate framework of SBCE's enablers and its implications for practice and theory .....	173
8.2	SBCE serious game and its implications for practice and theory .....	174
8.3	SBCE Innovation Roadmap (SBCE IR) and implications for practice and theory .....	177
8.4	Integrated framework of SBCE's enablers, SBCE serious game and SBCE IR – Synergies and future perspectives .....	179
	<b>PHD CANDIDATE PUBLICATIONS .....</b>	<b>181</b>
	<b>THESIS REFERENCES .....</b>	<b>184</b>



<b>APPENDIX.....</b>	<b>201</b>
<b>Appendix A1:</b> Semi-structured questionnaire used to assess the practices of SBCE in industries .....	201
<b>Appendix B</b> .....	204
B1: Trade-offs curves for Body, Wing, Cockpit, and Tail departments .....	204
B2: Checklists for Body, Wing, Cockpit, and Tail departments.....	205
B3: Limit curves for technical feasibilities.....	206
<b>Appendix C1:</b> Questionnaire for measuring the learning outcomes of the SBCE serious game .....	208

## Lists of Figures

Figure 1.1: Structure of the thesis. ....	3
Figure 1.2: Framework of SBCE serious game. ....	8
Figure 1.3: Schematic representation of SBCE IR steps.....	17
Figure 2.1: Generic phases of product development (Ulrich and Eppinger 2000).....	6
Figure 2.2: The design space representation (Sorensen 2006). ....	7
Figure 2.3: Schematic representation of a design – build – test approach.....	8
Figure 2.4: Schematic representation of a test – build – design approach. ....	8
Figure 2.5: Problem solving approach in PBSE – an example from an automotive development (Ward et al. 1995). ....	10
Figure 2.6: PBCE in automotive development (Sobek, et al. 1999).....	12
Figure 2.7: Committed cost and incurred cost as a design process progresses (Anderson 1997). ....	17
Figure 3.1: Conceptual schema of SBCE (Bernstein 1998).....	22
Figure 3.2: Intersections of possibilities help define specifications between Toyota and its suppliers (Sobek, et al. 1996). .....	25
Figure 3.3: Trade-off curve for Exhaust System in Toyota (Ward, et al. 2007). ....	26
Figure 4.1: Integrated framework of SBCE principles, process and enablers.....	34
Figure 4.2: Customer value research as enabler for SBCE process.....	38
Figure 4.3: People competence as enabler of SBCE process. ....	41
Figure 4.4: Product development matrix organization as enabler for SBCE process.....	42
Figure 4.5: Involvements and integration in SBCE process.....	46
Figure 4.6: Intra/ inter knowledge capturing documentation, transfer and use in SBCE process. ....	48
Figure 4.7: Problem solving approaches in TRIZ (Savransky 2000; Hua, et al. 2006).....	54
Figure 4.8: Integrated framework of SBCE and its enablers .....	61
Figure 5.1: Design paradigms followed. ....	69
Figure 5.2: Consideration of alternative and selection. ....	69
Figure 5.3: Mechanisms to capture knowledge in design. ....	70

Figure 5.4: Challenges in knowledge capturing and representations. ....	71
Figure 5.5: Research question on how to identify and prioritise areas for SBCE implementation. ....	73
Figure 5.6: Structure of the thesis. ....	77
Figure 6.1: Learning and innovation cycle (adopted from Knight 2002).....	81
Figure 6.2: A simplified airplane structure to be designed and the LEGO bricks used. ....	85
Figure 6.3: Framework of SBCE serious game. ....	86
Figure 6.4: Team building in stage-one of SBCE serious game. ....	88
Figure 6.5: Schematic diagram of the steps in stage-two of SBCE serious game. ....	92
Figure 6.6: Examples of trade-offs and checklists used in the game for mapping the design space for body dimensions (example from group 1). ....	93
Figure 6.7: Example of defining compatible body modules form group 1. ....	94
Figure 6.8: Example of a limit curve to evaluate alternative airplane structures (limit curve constructed from the testing constraint $23L \leq ws < L$ ). ....	95
Figure 6.9: Set reduction process in stage two of SBCE game – an example from group 1. ....	96
Figure 6.10: Descriptive statistics of declarative learning outcomes (N = 49, $\mu$ = mean and $\sigma$ = std. dev.). ....	100
Figure 6.11: Descriptive statistics of procedural learning outcomes (N = 49, $\mu$ = mean and $\sigma$ = std. dev.). ....	106
Figure 6.12: Descriptive statistics of strategic learning outcomes (N = 49, $\mu$ = mean and $\sigma$ = std. dev.). ....	109
Figure 6.13: Summated scales of SBCE enablers, performances improvements and implementation success. ....	113
Figure 6.14: Correlations between SBCE enablers, performance and implementation success ( $N=49$ , <sup>(#)</sup> $p \leq 0.10$ , <sup>(*)</sup> $p \leq 0.05$ , <sup>(**)</sup> $p \leq 0.01$ ). ....	116
Figure 7.1: Difference on accepting and overcoming trade-offs (modified from Hipple 2003). ....	127
Figure 7.2: Schematic representation of SBCE IR steps. ....	129
Figure 7.3: An example of House of Quality (HOQ) and the steps to build the SBCE IR (excerpt from the AHS case study, and note: n = no, y = yes, NA= data not available).....	130
Figure 7.4: Examples of priority rules of independent contradictions for SBCE implementation. ....	139
Figure 7.5: AHS sub-systems and components.....	141
Figure 7.6: Results from steps 1, 2, 3 of SBCE IR (Note: Y=yes, N=no, NA=data not available, (-) contradiction, ok=keep the current performance of the AHS design). ....	144

Figure 7.7: DEMTEL causal relations between contradictions in AHS. ....	149
Figure 7.8: Causal relations of dependent contradictions. ....	150
Figure 7.9: Independent contradictions and the rankings of corresponding contradictory requirements. ....	151
Figure 7.10: SBCE framework to overcome T21. ....	155
Figure 7.11: Rack components and mapping contradiction T21 to Rack design factors. ....	156
Figure 7.12: Limit curve for pressure test of mechanical drain valves and suppliers evaluation. ....	159
Figure 7.13: Benefits and synergies of SBCE IR and existing methods used in the case company. ....	163

## **List of Tables**

Table 1.1: Summaries and conclusions of the results of SBCE serious game measurement. ....	11
Table 1.2: Summaries of SBCE IR’s assessments by AHS experts. ....	1
Table 2.1: Comparison between problem solving approaches in PD. ....	9
Table 2.2: Comparison of PD performances of Toyota and other automakers (Clark, et al. 1987; Clark and Fujimoto 1989; Womack, et al. 1990). ....	16
Table 2.3: Comparison of PBCE and SBCE. ....	18
Table 3.1: Comparison of SBCE with similar approaches. ....	30
Table 4.1: Some examples of customer value capturing methods. ....	36
Table 4.2: Example of methods that can support the process of exploring alternative sets of solutions in SBCE. ....	55
Table 5.1: Summary of industries surveyed. ....	67
Table 5.2: Research gap-one, objective and research methodologies followed/used. ....	72
Table 5.3: Research gap-two, research objective and research methodologies followed/used. ....	75
Table 6.1: Comparison of existing and SBCE serious games. ....	84
Table 6.2: Characteristics of a single point on a LEGO component. ....	84
Table 6.3: List of customer requirements in SBCE serious game for 8 groups. ....	87
Table 6.4: Fictitious testing constrains for SBCE game. ....	89
Table 6.5: Rules to measure total development cost in SBCE serious game. ....	90

Table 6.6: Rules to measure total development time in SBCE serious game.....	90
Table 6.7: Demographics of SBCE game players in the company (N = 49).....	98
Table 6.8: Questions for measuring the declarative (D) learning outcomes and summary of response results. ....	99
Table 6.9: The Mann-Whitney U tests for declarative learning outcomes (rejected hypotheses are reported).....	102
Table 6.10: The Mann-Whitney U tests for procedural learning outcomes (only rejected hypotheses are reported). ....	107
Table 6.11: Questions for measuring the strategic (S) learning outcomes and summary of response results.....	108
Table 6.12: The Mann-Whitney U tests for strategic learning outcomes (rejected hypotheses are reported).....	111
Table 6.13: Correlations between SBCE enablers, perceived performance improvement and implementation success ( $N=49$ , <sup>(#)</sup> $p \leq 0.10$ , <sup>(*)</sup> $p \leq 0.05$ , <sup>(**)</sup> $p \leq 0.01$ ).....	115
Table 6.14: Summaries and conclusions of the results of SBCE serious game measurement. ....	120
Table 7.1: The pairwise comparison scales (Saaty 1980, 2001, 2008). ....	132
Table 7.2: RI values for different matrix sizes (Forman 1990). ....	133
Table 7.3: Judgment matrix A for macro-requirements. ....	143
Table 7.4: Judgment matrix A for usability (U) micro-requirements. ....	143
Table 7.5: MATLAB procedure to determine weights for macro and micro-requirements and to check CR. ....	145
Table 7.6: Contradictions and the respective contradictory requirements. ....	146
Table 7.7: Direct-relationship matrix X of contradictions.....	147
Table 7.8: Normalized direct/indirect or total relation matrix F of contradictions. ....	147
Table 7.9: Causal influence level of contradictions. ....	148
Table 7.10: Normalized direct/indirect or total relation matrix $F_{\text{cut} = 20\%}$ of contradictions.....	149
Table 7.11: Mapping contradiction to AHS.....	153
Table 7.12: Summary of Non-VDI Rack concepts generated, advantages, disadvantages, and tests required. ....	158
Table 7.13: Summaries of SBCE IR's assessments by AHS experts.....	166



# 1 SYNTHESIS

The concept of set based thinking is originally proposed by researchers from MIT (Massachusetts Institute of Technology) and UM (University of Michigan) in the 90's. Allen Ward pioneered the conception of this revolutionary idea during his Ph.D. research. Then, he and his colleagues were looking for industrial evidence that can exhibit the set based approach to product design and development process. They stumbled with Toyota's product development (PD), which in many ways resembles what they later called SBCE (Set-Based Concurrent Engineering). Sobek, et al (1999) summarized the definition of SBCE as engineers and product designers "reasoning, developing, and communicating about sets of solutions in parallel and relatively independent". Moreover, through observations of Toyota's PD, they devised three principles of SBCE, *principles of exploration, set based communication, and convergence*. Regardless of its origin, SBCE is much more sensible approach to PD than most industries are practicing, especially at early phases of design. Design and development is a unique process, where products and knowledge are created, discussed and realized. However, in the current industrial context, many companies are suffering due to poor PD performances. Lack of innovation, project delays, cost overruns, poor qualities, knowledge wastes, and poor learning capabilities are among the challenges that industries are facing at the moment. SBCE, if integrated well, could significantly contribute to alleviate these challenges. It contributes to revolutionize companies to be true learning organizations. Through its principles, SBCE will guide designers and managers to orient themselves for the creation of high value products and strive to create usable knowledge in PD.

There is growing interests across industries to apply SBCE to improve their development performances. However, SBCE has not been well diffused as a PD practice in industries. The problems can be observed by looking at two gaps. The first one is related to the awareness level of SBCE by practitioners. In this thesis, I found that SBCE is not well understood and practiced by many designers and managers. Therefore, there is need for a method to introduce and to increase the awareness level of SBCE in industries. The second reason for the low diffusion is related to the extensive nature of SBCE to apply it for a product. To conduct a SBCE process for a product, designers should go through extensive phases (exploration of alternative sets, communication of alternative sets, test of alternative sets and converge to optimal sets). Doing all these requires considerable time, investment and capabilities. In particular, for some industries (e.g. medium sized companies and SMEs) the challenges will be aggravated due to limited resources and capabilities available to conduct SBCE. The original principles of SBCE are derived from big automakers (especially Toyota) which are in different business context than several other industries. At the present, in literature there is a lack of systematic methods for introducing and guiding practitioners where in a product system to apply SBCE. The gaps should be addressed for helping companies (medium sized companies and SMEs) to benefit from SBCE principles. The

main intent of this thesis is therefore to propose systematic methods to alleviate the aforementioned gaps existed in practice.

The first contribution of the thesis is related to the low awareness level by practitioners about SBCE. In this work, a learning method - called SBCE serious game - is designed and proposed to increase the awareness level of SBCE in industries. Gaming is very effective to introduce this novel model (SBCE) to practitioners. The game has been played by many designers and managers. The game has been effective to increase their understanding level of SBCE principles.

The second contribution is related to the extensive nature of SBCE to apply it for a product. In this thesis a methodology called SBCE Innovation Roadmap (SBCE IR) is proposed. The purpose of this methodology is to guide designers to identify and prioritize areas (subsystems, components or design factors) that have to be the target for SBCE implementation. The SBCE IR methodology argues that designers should make rational choices to start SBCE implementation projects. Moreover, SBCE demands a rational and careful investigation a priori to identify where SBCE should be applied and use it to benefit customers with better product and increase value to the company. Otherwise, random efforts made on SBCE might be wasted without achieving the desired value. The SBCE IR methodology advocates that SBCE should be made in incremental manner rather than at full product level. The SBCE IR methodology is tested and validated in a real company (Carel Industries) on a real product, an Adiabatic Humidification System (AHS) designed by Carel Industries.

In sum, in this thesis a SBCE serious game is developed to increase the awareness level of SBCE in industries. It is validated in a selected case company. Then, the SBCE IR methodology is proposed to guide designers to identify and prioritize areas to begin SBCE implementation at product level. This methodology is validated in the same case company. SBCE serious game and SBCE IR are the main contributions this thesis offers to industries and make methodological contributions to SBCE's body of knowledge.

## **1.1 Thesis structure**

This thesis is structured as follows (Figure 1.1):

- Chapter 2 is dedicated to the introduction of PD and the available models used to design products. Moreover, in this chapter problem solving approaches in PD are presented and discussed in details. The emergence of SBCE in PD literature as well as its promising advantages in alleviating the limits and risks of existing PD models such as Point Based Serial Engineering (PBSE) and Point Based Concurrent Engineering (PBCE) is discussed and summarized.



- In chapter 3, the concepts and principles of SBCE are introduced. Comparisons between SBCE and seemingly similar existing models are also discussed in this chapter.
- In chapter 4, enablers of SBCE are identified and discussed and put into framework. Extensive literature review has been made to construct and rationalize the importance of the enablers for successful implementation of SBCE principles industries. Finally, in the chapter, the integrated framework of SBCE is presented.
- In Chapter 5, the research gaps identified, the thesis objectives and research methodologies followed for PART I and PART II of this thesis are presented. The rationale behind the research gap one and two are discussed in details in the chapter.

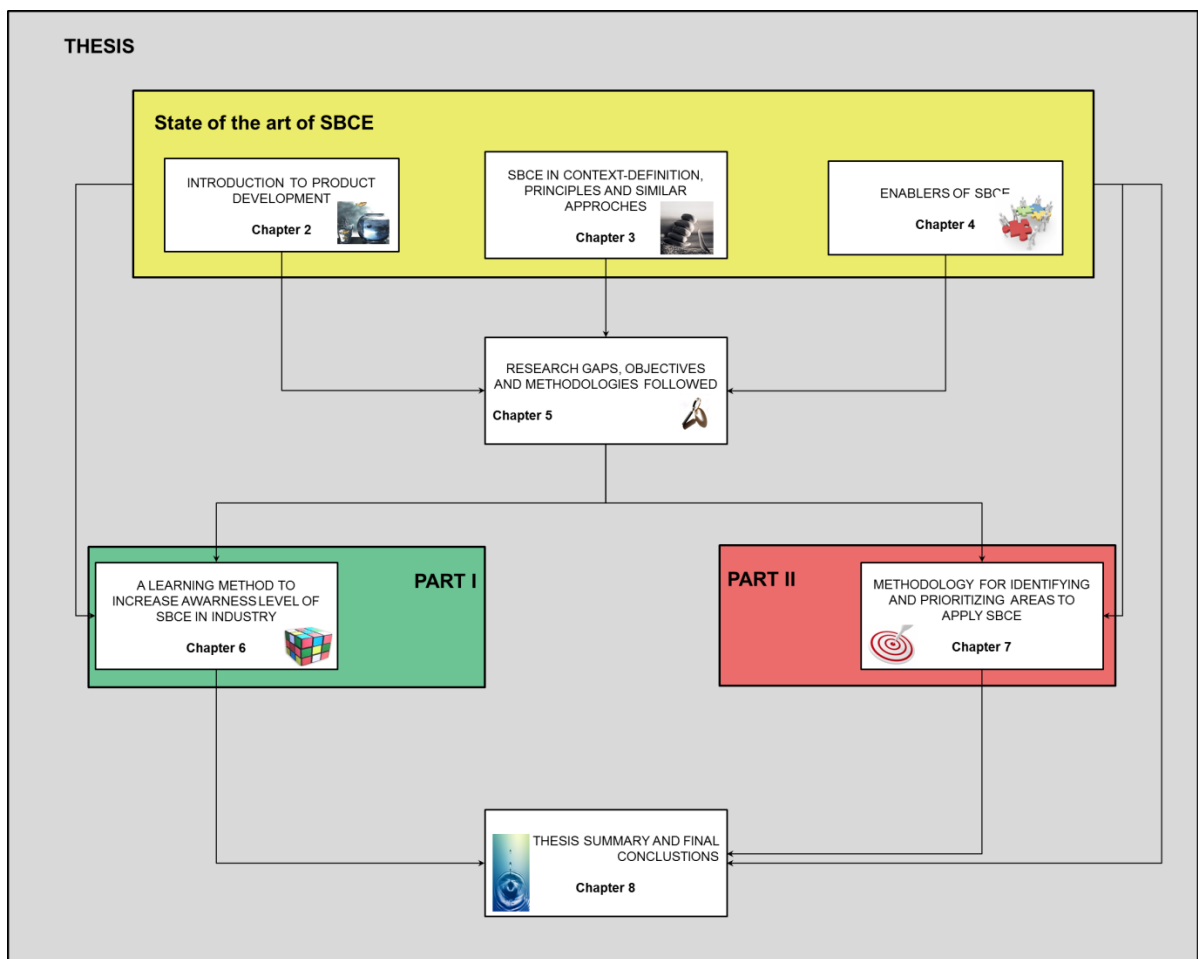


Figure 1.1: Structure of the thesis.

- Chapter 6 is dedicated for PART I of this thesis, where the learning method SBCE serious game is introduced and validated in the case company. In this chapter, the state of the art of serious gaming and the existing games in literature targeting concurrent engineering are also analyzed. The detail

steps of the measurement of the learning outcomes and the results obtained are discussed in great detail. Furthermore, the summaries, conclusions and future researches related to the chapter are illustrated.

- Chapter 7 deals with the PART II of this thesis. In this chapter, the criteria, assumptions and logics considered to build the SBCE IR methodology will be discussed. The steps of the SBCE IR methodology will be explained in detail. The description of the case product (AHS) is introduced in this chapter. The validation of the SBCE IR methodology in AHS case is also presented. The SBCE process and the results found related to the SBCE experimentation on Rack subsystem is presented in detail. Moreover, the experts' assessment on the effectiveness, applicability and limitations of SBCE IR is presented in the chapter. Furthermore, the summaries, conclusions and future researches related to the chapter are illustrated.
- Chapter 8 briefly summarizes and concludes the thesis as a whole.

The remaining of this chapter summarizes the contents and research background of the thesis. In section 1.2, the two parts (PART I and PART II) of the thesis are briefly summarized. The summary includes the research gaps, objectives and research methodologies followed to address the gaps. Moreover, the SBCE serious game and SBCE IR methodology are briefly introduced. The summaries of the results found from the validations are also included in section 1.2. Moreover, future possible researches are also outlined.

## **1.2 Research background**

This thesis begins by reviewing the state of the art of SBCE. Chapters 2 and 3 are dedicated to introduce SBCE definition, principles and the comparisons of other similar approaches in product development. In these chapters, the importance of SBCE to improve the shortcomings of traditional PD models is also discussed. In chapter 4, this paper provides an integrated framework of SBCE enablers. Enablers are those strategies, organizational practices, tools, methods, and technologies that are necessary to execute principles of SBCE. Extensive literature review has been conducted to build the framework. The review includes literature from product design, knowledge management, tools, methods, technologies, and concurrent engineering bodies of knowledge in product development. The integrated framework has two purposes. The first purpose is in contextualizing SBCE. Principles of SBCE cannot be effectively applied in PD without the exciting of these enablers. Thus, the framework shows a holistic view of SBCE with its principles along with the enablers. The second purpose is to use it to design the SBCE serious game. The game has been designed taking some of the enablers of SBCE such as tradeoff curves, limit curves checklists. These enablers are embedded in the game to educate industrial players on how to use them to explore alternative sets,

communicate alternative sets and evaluate sets to converge into an optimal one. Of course, for simplicity purpose all the enablers identified in chapter 4 are not embedded in SBCE serious game but only some. Moreover, some of the enablers are also used to develop the SBCE IR methodology. For example, Quality Function Deployment (QFD), Analytical Hierarchical processes (AHP), Theory of Inventive problem solving (TRIZ) are some of the enablers used in constructing the SBCE IR methodology.

Then, the thesis is partitioned into two parts (PART I and PART II). The following section 1.2.1 summarizes PART I, which dealt with the first gap (low level of awareness about SBCE in industries) identified in this thesis. Moreover, this part discusses the objective, research methodology followed to fill the gap and achieve the objective. Furthermore, brief discussions about SBCE serious game and the results from the validation are also presented in section 1.2.1. Section 1.2.2 summarizes PART II of the thesis, which dealt with the second gap (there is a lack of a systematic methodology to identify and prioritize areas for SBCE implementation). Moreover, this part discusses the objective, research methodology followed to fill the gap and achieve the objective. Further in section 1.2.2, brief discussions about SBCE IR methodology and the results from the validation on AHS case are also presented.

## **1.2.1 PART I – A learning method to increase awareness level of SBCE in industry**

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### **Research gap one and objective**

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The first research *gap* is related to the *low awareness level of SBCE in industries*. The level of awareness in this thesis can be interpreted into four aspects: *i) the principles and enablers of SBCE are new to companies, ii) the diffusion and practice of SBCE principles and enablers are low in industries and iii) the advantage/hurdles of implementing SBCE principles and enablers are not well understood by industries*. In this thesis, it is found out that most of the practices across industries are predominately point based concurrent engineering (PBCE). This gap has been reported from previous researches. For example, Bernstein (1998) conducted multiple case studies in aerospace industries in the U.S. The study reported that, in many of the aerospace industries, the application of SBCE is very limited and there is a low awareness level across the industries. Similarly, a recent study conducted in Swedish industries showed similar results, SBCE are not well understood and implemented (Raudberge, 2010). This study shows that companies trying to adopt SBCE observed negative results. For example, in some industries there were a 25% increment in lead time and a 25% increment in development cost. Some firms obtained neither gains nor losses in adopting SBCE. Those companies who obtain negative results and those who had zero loss/gain were asked about the rationale of

the results. Most companies answered “**SBCE is not the way they normally used to work**” (Raudberge, 2010).

Moreover, in this thesis a preliminary field study has been conducted to see if SBCE’s principles and enablers are practiced in companies operating in Italy. The study is conducted based on semi-structured questionnaire and face-to-face interviews with product designers and managers working in 19 different industries. The result shows that SBCE is not practiced and understood by most companies. The design paradigm followed by most companies resembles a point based approach where a single alternative is selected from early phase of design. Moreover, design knowledge is not well captured and documented to be used in future projects to explore, and evaluate alternatives. According to the study, these usually lead companies to incur high rework costs and miss targets (in terms of customer expectation and cost target). See section 5.2.2 for more details on the results from the field study.

Thus, in this thesis, this gap is taken as an important issue to be addressed. If there is a way to increase the level of awareness across industries, it brings contributions primarily to the industry to increase their awareness level and evaluate the applicability of SBCE in their design practices. Since there is a growing interest to adopt SBCE in industries, tackling this gap becomes paramount.

The main *objective* of this thesis is therefore to *develop a learning method to introduce SBCE principles and enablers to practitioners*. In this thesis such a method called SBCE serious game is developed and validated.

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## Research methodology followed

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- *Methodology followed to design a learning method*

In order to develop a learning method a serious gaming (SG) approach is used. The learning method which is designed in this thesis is called SBCE serious game (SBCE SG) which is aimed at introducing the principles and enablers of SBCE in a simple and engaging manner to increase the awareness level in industries. Serious games can be defined as ‘the application of games which are aimed at education and learning’ (Wouters, et al. 2007). There are six characteristics that make a serious game as an effective approach to introduce new and complex concepts as SBCE: (1) *internalize knowledge without interfering in an actual practices* (Prensky, 2001), (2) *improve communication* (Geurts and Joldersam, 2001), (3) *create consensus*, (4) *commitment to action* (Mayer, 2009), (5) *stimulate creativity* and (6) *simulate complexity* (Duke and Geurts, 2004). Such opportunities are rare in traditional methods such as lectures based on handouts (which are normally ineffective in giving hand-on experiences) or case studies (which lack in giving feedbacks before

actual implementation). That is why in this thesis serious game is taken as method to develop the learning method for SBCE, and eventually improve the effectiveness of the learning outcomes.

- *Methodology used to validate the learning method (SBCE SG)*

After the SBCE SG is designed, validation of its effectiveness is measured. A structured questionnaire based on Garris et al. (2002) framework is developed. This framework is the most prevalent framework in measuring the learning outcomes or effectiveness of a serious game. The framework divide learning aspects of games into three: *declarative learning*, which is concerned with the effectiveness of a game in transferring the underlying theories embedded in the game; *procedural learning*, which deals with the measurement of the abilities of players in understanding complex patterns embedded in the game; and *strategic learning*, which measures the intellectual abilities and willingness of players to adopt what is though in the game to real-life problems. The questionnaire contains 26 questions grouped in the three learning aspects. The questions are formatted in Likert five scale scheme (Likert 1932). The game has been played by 60 highly experienced engineers and managers working in Carel Industries ([www.carel.com](http://www.carel.com)). The company is operating in Italy developing products for HAVC/R market. Given that the company operates in different context than big OEMs where SBCE has been originated, the feedback from the game can reflect the applicability of SBCE in different industrial context (e.g. in medium sized companies or SMEs). After playing the game in the company, it has been possible to measure the learning outcomes using the questionnaire provided. Using appropriate descriptive and inferential statistics the effectiveness of the game has been measured. Moreover, interesting insights are gained concerning the perceived advantages of SBCE in this particular company and the practical hurdles that engineers/managers anticipate in adopting it in reality.



## **SBCE serious game**

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In SBCE serious game, players have to design an airplane structure which has four subsystems (body, wing, cockpit and tail). The game is played in a team of four players and each player in a team represents a subsystem department (body, wing, cockpit and tail). Airplane structure is chosen as a game element because of its complexity. Since each subsystem is designed by a player in a team, it creates sufficient complexities concerning exploration, communication and evaluation of sets. Thus, using the airplane structure, it has been possible to create an environment where SBCE can be simulated. The players will be provided LEGO components to design their subsystems. LEGO components have points on the top which have properties (cost, ordering time, weight, length and width). Moreover, players will be given customer requirements to satisfy. The game is divided into two stages: Stage one, where players design an airplane structure for a

given list of customer requirements following PBCE process; and Stage two, where players have to design the airplane structure following SBCE process.

The first stage is not supported by any SBCE enablers, rather industrial players have to design following their logics and norms in their company. Once they finished their first prototype in this stage, players have to submit their prototype to “testing department”. The game facilitator/ s acts/ act as a testing department. If the submitted airplane fails to meeting customer requirements and/or the constraints of testing department, players have to redesign their airplane. In this case, they will be penalized on time (due to not meeting customer requirement) and rework time (due to failing constraints). The testing constraints are not given to players for the first trial. After trails, if the prototype passes the customer requirements and testing constraints, players will be given their performance in terms of total development time and cost. Then, they pass to the second stage.

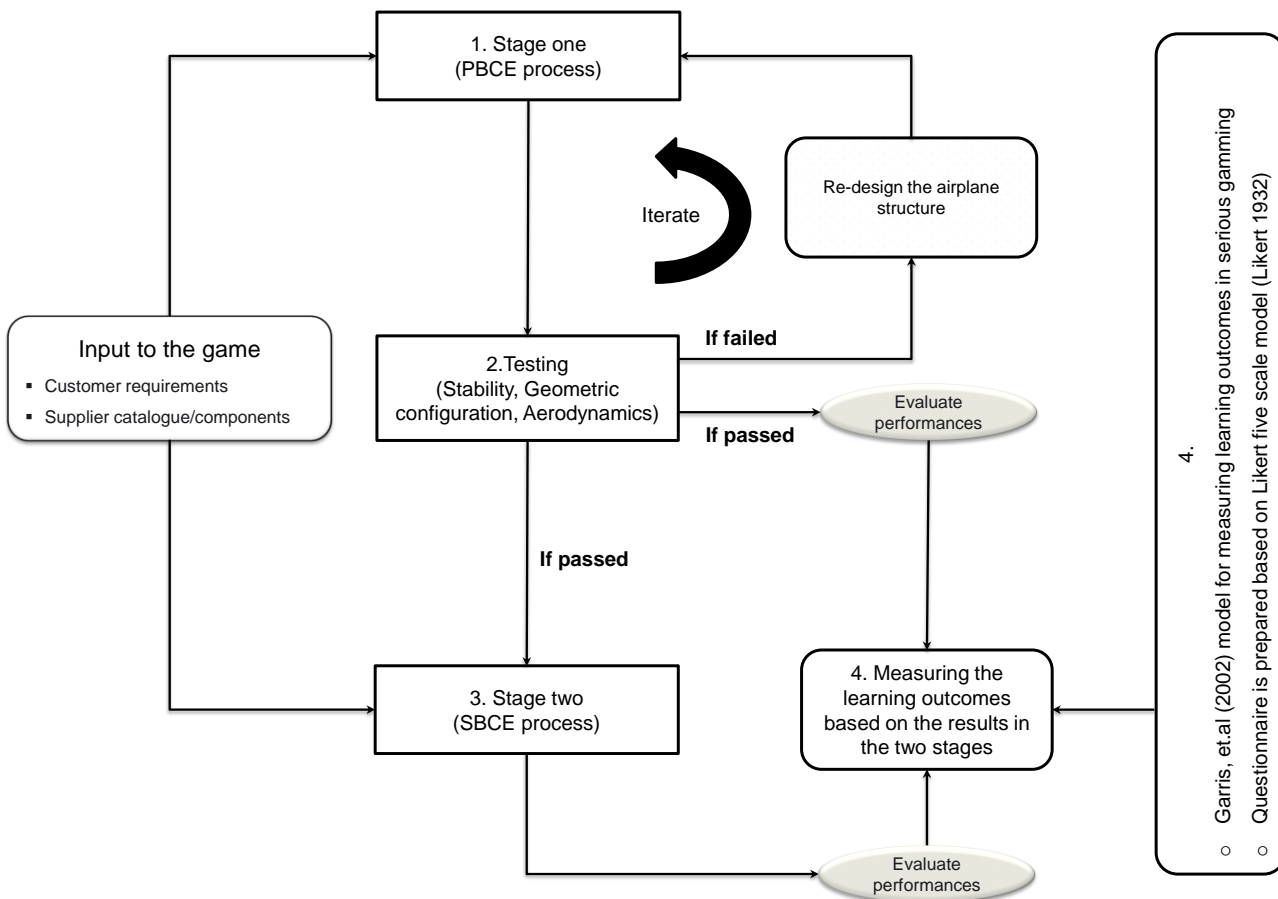


Figure 1.2: Framework of SBCE serious game.

In Stage two, players are provided with the necessary enablers of SBCE to simulate an environment where designers presuming to design an airplane structure following SBCE process. The enablers will help players to explore alternative design concepts, communicate about alternative solutions within a team, and converge

into a preferred (a high value) airplane structure. Tradeoff curves, limit curves and checklists are provided as SBCE enablers to players at this stage. This stage is automated with Excel program.

In between the two stages, the facilitator/s of the game introduce about the principles and enablers of SBCE. Discussion will be held to identify the key drawback of PBCE and how SBCE can benefit to avoid them.

Once players finish the two stages, the teams' performances in the two stages will be given and discussion will be made. Moreover, the structured questionnaire (based on 'Likert five scale' scheme) will be given to the players to give feedback on the effectiveness of the game as well as to reflect the applicability of SBCE in their real design practice. The questionnaire is developed to measure the three learning outcomes (*declarative, procedural and strategic* learning outcomes). The general framework of the game design is presented in Figure 1.2.

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### **Results obtained from validation of SBCE serious game in industry**

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The game has been played by designers and managers of Carel Industries who designs and manufactures products in HVACR (Heating, Ventilation, Air-conditioning and Refrigeration) market. In total, there were more than 60 players who played the game in the company, but only 49 responded to the questionnaire provided. Therefore, the measurement of the learning outcomes is based on 49 designers (Mechanical, Electrical, and Software designers) and managers (product managers and project leaders) who give responses to the questionnaire provided.

To analyses the learning outcomes of playing the game with the industrial players, first basic descriptive statistics are used ( $\mu$ , mean and  $\sigma$ , standard deviation). These analyses are made for each learning outcomes measures (*declarative, procedural and strategic*). Then, inferential statistics are made for each learning outcome measures to identify group differences (designers vs. managers, highly experienced vs. less experienced, female vs. male and older vs. younger players). To execute inferential statistics, the prevalent Mann-Whitney U test is used which is appropriate for ordinal data (Likert scale) (Siegel 1957; Newson 2001).

Finally, to generalize the lesson learned from the game play, the questions from different learning outcome measures are regrouped to create valid summated scales that have theoretical and practical implications (Spector 1992). To measure the reliabilities of the summated scales, Cronbach alpha threshold ( $\alpha \leq 0.7$ ) is used (Cronbach 1951; Cronbach, et al. 2004). By iterative assigning the questions and checking the reliabilities, six valid and reliable scales are defined. These scales are: *Tool (T)*, which is defined as the understanding and use of tools (tradeoff curves, limit curves and checklists) in SBCE; *Involvement (INV)*,

which is defined as the understanding and integration of stakeholders (e.g. customers and testing department) in SBCE; *Communication (C)*, which is defined as the recognition, understanding and benefit of adopting set based communication (i.e. communicating based on sets or alternatives or rough information); *Knowledge building (K)*, which is defined as the identification, capturing and representation of design related knowledge in SBCE; *Performance (P)*, which is defined as the performance improvement potentials of the SBCE enablers such as Tools (T), Involvement (INV) and Communication(C) and Knowledge building (K); and *Implementation (IMP)*, which is defined as the capability of a company to be adept in problem solving and becomes a learning organization.

Once these scales are defined Spearman's rho ( $\rho$ ) correlation coefficient is used, which is appropriate for ordinal data (Likert scale) (Siegel 1957; Newson 2001). The rho ( $\rho$ ) correlation coefficient between the scales can determine which of these scales are significantly correlated and can deduce the general lesson learned from the game play in this particular case company.

The results of the game measurement of in the case company are summarized in Table 1.1.

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## Future researches

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- *Future research related to SBCE serious game deign*

There are limitations related to the design of the SBCE game. The current version of the game contains only certain enablers of SBCE process. However, there are other enablers that are interesting to be included (e.g. organizational aspects, people competences, chief engineering system and so on). Therefore, future research might focus on improving the game to include other enablers of SBCE.

- *Future research related to game measurement and validation*

There are limitations on the validation and consequently on the results found. Although, the SBCE game has been a success in this particular company, it needs to be introduced to wider industrial players in different contexts. Moreover, the conclusions and implications listed in Table 1.1 are predominately based on the feedbacks from one company which specializes in HVACR market. If different industrial types are included a more solid and accurate results concerning the applicability of SBCE in industries can be developed. Therefore, future researches remain to validate the game with different other industrial players and compare the results across industries.



Table 1.1: Summaries and conclusions of the results of SBCE serious game measurement.

Learning outcomes	Results obtained from game measurement and feedbacks from industrial players	Rationales	Implications for practice and theory
<b>DECLARATIVE LEARNING OUTCOMES</b>	<p>SBCE serious game has been effective to introduce SBCE's principles and enablers embedded in the game.</p>	<ul style="list-style-type: none"> <li>The game is designed to educate SBCE and comparison between PBCE is made. Tradeoff curves, checklists and limit curves have been embedded in the game to facilitate the SBCE in designing a simplified airplane structure.</li> </ul>	<ul style="list-style-type: none"> <li>The game can be used to educate practitioners to increase their awareness level about SBCE.</li> </ul>
	<p>Principle of set based communication and tools to facilitate it might not be critical in this company.</p>	<ul style="list-style-type: none"> <li>Products in HAVC/R market do not involve complex and integrate subsystems like automotive designs (where set based communications is key).</li> <li>Small design team members for a design project.</li> <li>Difficulties of communicating design sets with suppliers.</li> </ul>	<ul style="list-style-type: none"> <li>Set based communication might not be a key principle of SBCE when: there is no- design complexity, number of designers in a project is very small and when suppliers are not willing or capable of communicating in sets.</li> </ul>
	<p>Designers and managers have different level of understanding of SBCE as presented in the game. Managers have higher awareness of SBCE than technical designers.</p>	<ul style="list-style-type: none"> <li>Managers have pre-information about SBCE from reading lean product development books, attending seminars and conferences.</li> <li>Managers have more ambitions for change.</li> </ul>	<ul style="list-style-type: none"> <li>If the differences arise because managers are pre-aware about SBCE, that will cause less problem during a real implementation phase.</li> <li>However, if the differences arise from "cultural" issues, that is, if designers don't appreciate new way of working than the norm, then, it will be difficult for managers to disseminate the concept of SBCE and obtain a wider acceptance in the company.</li> </ul>
	<p>There is a significant difference between</p>	<ul style="list-style-type: none"> <li>Less experienced designers in the company indicated</li> </ul>	<ul style="list-style-type: none"> <li>Experience matters to understand and effectively deploy SBCE.</li> <li>Tools used in SBCE serious game</li> </ul>

	highly and less experienced players in perceiving SBCE.	<p>that there are difficulties to anticipate design problems at the frontend of a design project, and the SBCE tools provided in the game has been appreciated to alleviate this problem.</p> <ul style="list-style-type: none"> <li>• Highly experienced players also indicate the importance of adopting SBCE tools to capture and transfer their knowledge to less experienced designers.</li> </ul>	has been perceived as very important to capture knowledge and knowhow and further transfer to less experienced designers.
<b>PROCEDURAL LEARNING OUTCOMES</b>	Industrial players have perceived significant benefits of SBCE in improving performances such as: reduction of risks, reduction of product/process costs, facilitates learning, improving quality.	<ul style="list-style-type: none"> <li>• The SBCE serious game provides a performance measurement scheme to compare PBCE and SBCE. During the play significant performance improvements have been demonstrated.</li> <li>• Players have also give feedbacks on the performance benefits of SBCE if it is applied in their real design practice.</li> </ul>	<ul style="list-style-type: none"> <li>• SBCE is beneficial for industries in improving performance measure of product development.</li> </ul>
	SBCE as portrayed in SBCE game or in literature has a limitation in enhancing innovation.	<ul style="list-style-type: none"> <li>• Innovation is perceived by the industrial players as an achievement of new design solutions which are unexpected.</li> <li>• However, the use of tradeoffs in SBCE as an exploration tool restricts the level of innovation. Because tradeoffs are based on accepting compromise rather than advancing performances to new levels.</li> <li>• Moreover, generating tradeoffs are difficult in practice.</li> </ul>	<ul style="list-style-type: none"> <li>• If tradeoffs are used for exploring alternatives in SBCE, it might limit the level of innovation that can be achieved. Therefore, exploration of concepts or generation of ideas has to been supported by other established innovation theories such as TRIZ to enhance innovation in SBCE process.</li> </ul>
	Managers have higher perception on SBCE's potential	<ul style="list-style-type: none"> <li>• Managers have more tendencies to accept SBCE as performance enhancer.</li> </ul>	<ul style="list-style-type: none"> <li>• Managers should convince technical personnel on the real value of SBCE either by taking pilot projects or introducing them</li> </ul>

	benefits for performance improvements than technical designers.	<ul style="list-style-type: none"> <li>Managers have more ambitions for change.</li> </ul>	with success stories from other industrial cases.
<b>STRATEGIC LEARNING OUTCOMES</b>	Thanks to the game, most practitioners are willing to adopt SBCE in their design practice.	<ul style="list-style-type: none"> <li>Most players acknowledge that playing the game has been worthwhile for their design practice</li> <li>Most players acknowledge that playing the game help to have ideas on how to practice SBCE enablers embedded in the game.</li> </ul>	<ul style="list-style-type: none"> <li>The game has been effectiveness in convincing players to adopt it in their daily practice.</li> <li>The game also helps on giving ways in how practitioners can execute SBCE in practice.</li> </ul>
	Generating tradeoff and limit curves are challenging in practice.	<ul style="list-style-type: none"> <li>Companies like this have limitations in resources to invest on simulation and testing tools to generate tradeoffs and limit curves. Moreover, generating alternative designs and building prototypes in parallel will be costly for these companies to capture and analyze governing performances data about sets.</li> </ul>	<ul style="list-style-type: none"> <li>SBCE should be taken as a process and as a journey where knowledge is systematically captured as a long term strategy. Developing tools, involving stakeholders, and effective communication should be in place to build knowledge. Then, performance benefits can be shown as a result and companies can successful implement SBCE and develop products in a knowledge based environment.</li> </ul>
	Managers have higher interests to adopt SBCE than technical designers.	<ul style="list-style-type: none"> <li>Managers have more ambitions for change and implement new concepts.</li> </ul>	<ul style="list-style-type: none"> <li>Care should be taken by managers before going to real implementation of SBCE and should obtain organization-wide awareness about the benefits of SBCE.</li> </ul>
	There is significant difference between highly and less experienced players in their ability to adopt SBCE in practice.	<ul style="list-style-type: none"> <li>Less experienced designers need coaching and mentoring on how to explore, communicate and evaluate sets. In playing the game, less experienced layers indicated challenges for them to adopt SBCE in their design practice.</li> </ul>	<ul style="list-style-type: none"> <li>Competence development is very important before implementing SBCE in practice. Highly experienced designers should do coaching and mentoring on how to conduct SBCE to less experienced engineers.</li> </ul>

<b>SUMMARY OF DECLARATIVE, PROCEDURAL AND STRATEGIC LEARNING OUTCOMES</b>	SBCE enablers such as tools, involvement, and communication are significantly correlated.		<ul style="list-style-type: none"> <li>• Tools such as tradeoff curves, checklist and limit curves helps in SBCE to effectively involve stakeholders (customers and internal function e.g. testing department). Moreover, the tools help to facilitate communication between subsystems departments to evaluate sets for compatibilities and feasibilities issues.</li> </ul>
	Except set based communication, SBCE enablers such as tools, involvement are significantly correlated with knowledge building.	<ul style="list-style-type: none"> <li>• Set based communication has been perceived less significant in the case company as knowledge building mechanism because of: few designers are involved in new projects and knowledge is centralized in few experts. Furthermore, price based relationships with suppliers dictates point based communication.</li> </ul>	<ul style="list-style-type: none"> <li>• For set based communication to commence in practice, trust between suppliers or partners should be build, so that sets can be explored and communicated.</li> <li>• Price based relations between developers and partners restrict the level of sets to evaluate and limit the possibility to discover and develop knowledge about the performance of alternative solutions.</li> <li>• When few or one designer is responsible for a project (common in smaller companies) tools to enable set based communication with team members to evaluate sets might not be important.</li> </ul>
	Implementation of SBCE should be taken as a journey.		<ul style="list-style-type: none"> <li>• In order to improve performance using SBCE enablers, the understanding and adoption of SBCE enablers are important. But, it needs efforts and investments to effectively build an organization that manage and share knowledge to develop products.</li> </ul>

## 1.2.2 PART II – Methodology for identifying and prioritizing areas to apply SBCE

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### Research gap two and objective

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The second research *gap* is related to *the lack of a methodological approach to identify and prioritize areas where SBCE can be implemented* (at a product level). The argument that rationalizes the methodological gap is the extensive nature of SBCE. To conduct an SBCE process, designers should go through extensive phases (exploration of alternative sets, communication of alternative sets, test of alternative sets and converge to optimal sets). Doing all these requires considerable time, investment and capabilities. For example, Terwiesch et al. (2002) and Bogus (2005) underscored the extensive nature of SBCE strategy, and asserted that it should be used when the cost of pursuing it is cheaper than to the value it can create. Ford and Sobek (2005) also proposed a real option model to find optimal number of sets to consider; limiting the efforts needed to conduct SBCE. Thus, SBCE's adoption should not be based on a random choice, and there is not a guarantee that any such initiative will be a success (Raudberge 2010, pp.690). In particular, the technological capabilities and methodological readiness and resources availability to fasten SBCE process are scarce in companies (e.g. medium sized and SMEs) (Raudberge 2010; Rossi, et al., 2011/b). In these situations companies need to focus their efforts on areas of improvement where SBCE will bring its utmost benefits. Therefore, there is a need for a systematic methodology to identify and prioritize subsystems or components a priori of pursuing such an extensive process. Otherwise, efforts made will be wasted without achieving the desired value.

The main research *objective* in this part of the thesis is therefore *is to develop a systematic methodological approach that can be used to identify and prioritize product subsystems for SBCE implementation*. In this thesis, such a methodology called SBCE IR (SBCE Innovation Roadmap) has been developed and validated.

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### Research methodology followed

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- *Methodology followed to develop SBCE IR methodology*

The methodology followed to build SBCE IR follows two steps. First, criteria and related assumptions that are required to build the SBCE IR have been defined. Second, existing methods and tools that are needed to execute the steps of SBCE IR are identified (see the SBCE IR section to see the methods and tools identified to build SBCE IR).

The following criteria and related assumptions are considered:

- (a) *The process of overcoming contradictions will follow SBCE process*, SBCE IR methodology is constructed based on the assumption that identification and overcoming of contradictions lead to design improvements. The assumption is based on the prominent theory of innovation called ‘Theory of Inventive Problem Solving’ or in short TRIZ (Altshuller 1984). TRIZ claims that overcoming contradictions lead to genuine innovations and it provides ways to arrive to design solutions (Altshuller 1984). SBCE IR takes the synergies between TRIZ and SBCE process. Thus, TRIZ’s concept of contradiction enables SBCE IR to identify improvement areas, where as SBCE’s principles will follow to overcome the contradictions by exploring design solutions, communicating solutions to team members and finally converging to an optimal final design concept. This means, contradictions will be input to begin SBCE processes.
- (b) *The area of improvements should be valuable for customers*: there could be several contradictions in a product system. However, all contradictions will not have same importance. Once contradictions are identified evaluating them for customer importance is taken as a criterion (i.e. how important it is for customers to overcome a contradiction?).
- (c) *The area of improvements should give competitive advantages*: in addition to taking customer importance as a criterion to prioritize contradictions, competitive advantage is also taken as another criterion (i.e. how much competitive advantage a company can get by overcoming a contradiction?). This criterion is needed since customer importance is not always the only source of that can be used to identify design improvements. Thus, analyzing competitors’ products should also be used as one criterion to build SBCE IR.
- (d) *The area of improvements should be achievable with respect to the resources available*: this is an optional criterion to build SBCE IR. However, it is very important to consider. Since overcoming different contradictions require different levels of resources or efforts, designers should balance the importance of overcoming a contradiction with respect to the resources/capabilities available in a company.

- *Methodologies used to validate the SBCE IR methodology*

Once the steps of the SBCE IR are defined and the necessary tools and methods are identified, three validations are conducted. Firstly, a case study on Adiabatic Humidification System (AHS)<sup>1</sup> is conducted to

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<sup>1</sup> This case study on AHS has been conducted in the same company the SBCE serious game has run ([www.carel.com](http://www.carel.com)).

test the methodology. Secondly, using the SBCE IR constructed for AHS system, a subsystem called Rack<sup>2</sup> is chosen to further experiment on how to start an SBCE and to improve the current Rack design.

Thirdly, pros and cons of the SBCE IR (e.g. advantages compared to existing methods used in the company, applicability, effectiveness, limitations, scalability, skills required etc.) have been assessed by conducting interviews with designers and project managers involved in the case study for AHS. An open questionnaire is provided. Interviews are made with four experts in the company who are well experienced and have technical, managerial and market competences. These experts have been extensively involved in collecting data and building SBCE IR for case product (AHS).

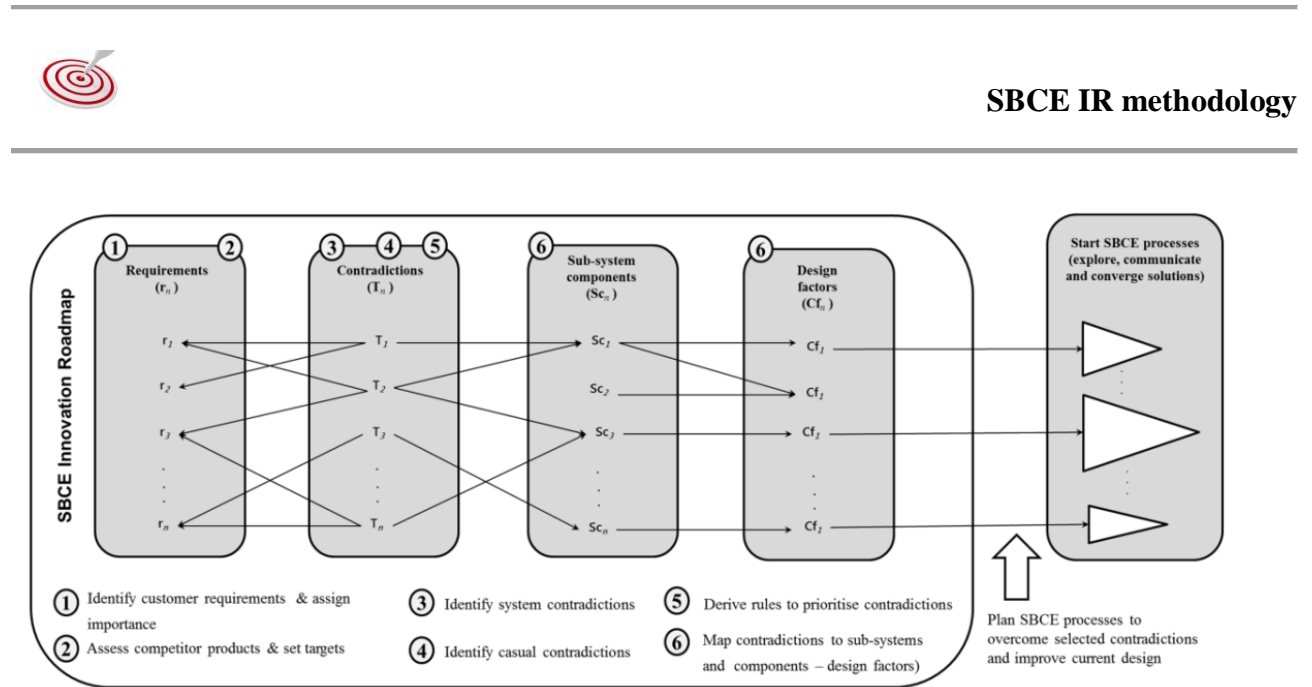


Figure 1.3: Schematic representation of SBCE IR steps.

The SBCE IR involves six steps (Figure 1.3) and each step is supported by common tools and methods found in literature. To structure the steps of the SBCE IR, QFD (Quality Function Deployment) method is used (Hauser and Clausing, 1988; Akao and Mazur, 2003). The first step is to identify customer requirements and assign importance. AHP (Analytical Hierarchical Process) is used to assign weights to customer requirements (Saaty 1980). The second step is to assess competitors' products and set targets for each requirement (Nieuwkuyk and Rogosch 1997). The third step is to identify technical and physical contradictions in a product system. The fourth step is to identify causal relations between contradictions to

<sup>2</sup> Rack is a subsystem of AHS used to distribute water to an ambient (refer section 7.3.2 for details).

sort out dependent and independent contradictions<sup>3</sup>. In a product system, some contradictions are highly related, and as a result overcoming a contradiction might eventually solve another contradiction. Moreover, there could be direct and also indirect (like transitivity) causality relations between contradictions. Therefore, DEMATEL (Decision Making Trial and Evaluation Laboratory) method is used to find such causal relations between contradictions (Fontela and Gabus 1974, 1978). In the fifth step, rules are derived to prioritize contradictions based on the information obtained from previous steps. For dependent contradictions, the roots will be given high priority for SBCE implementation. This is because overcoming root contradictions<sup>4</sup> is more efficient. For independent contradictions rankings of their contradictory requirements are used to prioritize them for SBCE implementation (derived from steps 1 and 2). The final step is to map prioritized contradictions to design factors (subsystems, components, and features) to being SBCE process to improve a product by overcoming contradictions. This final step should be done by experts designing and developing the product.

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### **Results obtained from validation of SBCE IR in AHS**

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The SBCE IR is validated taking the AHS system as a case. AHS system is a product that is used primarily for industrial applications (such as hospitals, residential buildings, textile factories, paint shops in car industries, and so on). The main function of the system is to control the temperature and humidity levels of a room or a working environment. The product is the state of the art among other humidification systems in terms of energy savings. The working principle is based on spraying atomized water mists to air at high pressure (around 70 bars) whenever the temperature and humidification levels are not desirable; that is how it gets its name, adiabatic refers to a very high pressure used to spray atomized water. The basic sub-systems are three Cabinet (C), Drop Separator (DS), and Rack (R). The researcher spent 6 months in the company to collect data to build the SBCE IR for the AHS system. Designers of AHS system have been involved in each step for data collection and also make sure the accuracy of the data. In total, 23 contradictions (22 technical and 1 physical) are identified and prioritized for further SBCE implementation.

Then, among all the contradictions, the AHS experts select a contradiction called ‘non-VDI rack’. This contradiction is a physical one, where it contradicts with itself. The contradiction is explained as follows:

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<sup>3</sup> Dependent contradictions are those contradictions which have causal relationships (for example, if overcoming a contradiction X, can overcome another contradiction Y, then X & Y are dependent and X is the cause and Y is the effect). However, if overcoming a contradiction X has no effect in overcoming Y (or vice versa), the two are independent.

<sup>4</sup> Root contradictions are those contradictions which are the cause to several other contradictions. For instance, if overcoming contradiction X, will eventually overcome contradictions Y & Z, then X is the root contradiction for Y & Z.



the current AHS design is compliant with European hygienic requirement called VDI6022. However, the company is expanding its business to different business applications or markets such as Tabaco industries, painting shops of automotive industries and in different emerging countries (e.g. China and Brazil). In this market (let's call this market as non-VDI market) there is no mandatory VDI6022 compliancy requirement and the current design is 'overly-designed' for this market. Moreover, these customers are requiring cheaper design and there are non-value adding features in the current design that have no value for non-VDI market. Therefore, the purpose of overcoming this contradiction is to satisfy both types of markets (VDI requiring market and non-VDI market). In order to overcome the contradiction, the company agreed to use the TRIZ "*principle of separation*" (Altshuller 1984, 1994, 1999). That is to separate the product version for two markets (VDI and non-VDI markets). This implies that, the current AHS design will be offered to VDI market and a new version has to be designed for non-VDI market.

Then, designers conducted an SBCE process (explore Rack concepts, concepts testing for constraints and finally converge into high value Rack concept). From the experiment, it has been possible to reduce the cost of the new Rack significantly. The cost advantages were obtained by looking for alternatives materials, removing non-value adding components and reducing unnecessary manufacturing and assembly operations. The company sees a potential in launching the new Rack to the market. This Rack concept is planned to undergo detail design phase and will be launched soon by the company.

However, the SBCE experiment focuses on overcoming one contradiction among the many others. Thus, the experimentation of SBCE on this contradiction doesn't necessarily validate the SBE methodology in terms of its advantages, applicability and limitations of the SBCE IR for the company. Therefore, an open questionnaire is prepared and interviews are made with four experts who are involved in the AHS case study.

The questions in the questionnaire are categorized in three classes: (i) differences and synergies with existing methods used in the company, this is to understand what is the existing method the company follows to identify improvement areas for new projects and investigate the differences and synergies with SBCE IR methodology; (ii) effectiveness of SBCE IR, this is to measure if the SBCE IR achieves its objectives in terms of reducing the extensive nature of SBCE process, its effectiveness to identify improvement areas for SBCE, its effectiveness in evaluating customer value, its effectiveness in evaluating competitors' products and its contribution to enhance innovation at early phase of design; and (iii) simplicity/ difficulties/ scalability/skills and capabilities needed to build SBCE IR, in this category the aim is to measure the efficiency of building the SBCE IR methodology in the case company. Interviews are made with four experts who are knowledgeable about technical, market, business and improvement related issues in the company. The interviews are made individually with each expert. The experts are extensively involved in building the steps of SBCE IR for AHS system and are knowledgeable about the existing practices in the company.

Table 1.2 summarizes the response of the experts in assessing the SBCE IR.

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## Future researches



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The following questions are proposed for future researches related to SBCE IR methodology:

- How to align SBCE IR with company's strategy for projects on new products and portfolio management process?
- How to improve SBCE IR to consider different types or levels of customers? And what are the impacts of having different customer types in solving contradictions using SBCE process?
- How to build SBCE IR for product modules or platforms? And what are the benefits in terms of stabilizing the SBCE IR and reducing the time it takes to build SBCE IR?
- How to simplify SBCE IR for small projects (new product with small improvements from the current design)? And, How to automate the SBCE IR for complex products to make the analyses involved in SBCE IR less time consuming?
- How to distribute contradictions to different development organizations? (For example, development organization in the case company is divided into two: product development, focusing on designing products upon customer request; and technology centers, which aim to develop new technologies and feed knowledge to the product development organization). Therefore, which contradictions to assign to which development organization is an open issue.

Table 1.2: Summaries of SBCE IR's assessments by AHS experts.<sup>5</sup>

Aspects	Questions	Summary of interviews responses
Difference and synergies with existing method used in the company	What is/are the current method/s to identify improvement areas for new products?	New market requirements, corrections of previous mistakes, technology push, company strategy that define the evolution of products, portfolio management to prioritize projects.
	How different existing methods are compared to SBCE IR?	<ul style="list-style-type: none"> <li>❗ Existing methods used in the company are not structured, difficult to plan for emerging/changing marketing requirements and correcting previous mistakes, technology push could also be random.</li> <li>❗ Existing methods are top-down approach and often have limitation in planning projects based on real customer benefits, competitors' analysis and resources availabilities.</li> <li>❗ Existing methods in the company are not focusing in contradictions rather they concentrate what is easy to change. This might limit the potential of offering innovative products to customers.</li> <li>✅ SBCE IR is proactive rather than reactive and improvements on products can be planned and resource requirements can also be anticipated beforehand.</li> <li>✅ SBCE IR is bottom-up approach in which designers and project managers can use SBCE IR to propose improvement projects to top management during strategic and portfolio planning.</li> <li>✅ SBCE IR can be integrated with existing methods. It helps to structure the existing methods (to effectively identify improvement projects) and support portfolio profiling or prioritizing.</li> <li>✅ SBCE IR is based on identifying contradictions and overcoming them using SBCE process. Focusing on contradictions is new way of working for the company but enables us to advance product technologies and excite customers and achieve higher market share compared to competitors.</li> </ul>
Effectiveness of SBCE IR	Does SBCE IR able to reduce the extensiveness nature of SBCE by prioritizing contradictions or tradeoffs as improvement areas?	<ul style="list-style-type: none"> <li>✅ Yes, SBCE IR helps us to define where innovation should takes place. Moreover, the prioritization scheme will help us to known what type of improvements or projects should be launched.</li> <li>❗ However, SBCE IR should be taken as a rough planning scheme, and then management should give more detail planning to prioritize contradictions based on company's strategy.</li> </ul>

<sup>5</sup>  positive feedback for SBCE IR;  limitation of existing methods used in the company or limitation of SBCE IR.

	Is SBCE IR effective in identifying improvements areas for SBCE	<ul style="list-style-type: none"> <li>✔ Yes, the first step of SBCE IR is to identify and assign importance of customer requirements. The AHP method used helps us to systematically weight the requirements to satisfy our customers.</li> </ul>
	Is SBCE IR effective in evaluating customer value?	<ul style="list-style-type: none"> <li>✔ However, customer requirements that are feed to SBCE IR should reflect the future needs of customers; otherwise the plan becomes unstable if customers frequently change their requirements. In order to make SBCE IR a robust planning methodology, designers and managers should study very well the current and emerging requirements in close collaboration with customers.</li> <li>❗ It is also important not to make inaccurate judgment about customers. Carel Industries is operating in a market where there are different levels of customer types (e.g. installers, contractors, OEMs and final customers). These customers usually have different importance for a requirement of a product. Therefore, in building SBCE IR the weighing of customer requirements should take care of balancing the needs of the different customer types.</li> </ul>
	Is SBCE IR effective in evaluating competitive products?	<ul style="list-style-type: none"> <li>✔ SBCE IR is effective in evaluating competitors' product. So that, we can make sure that we stay competitive in the competitions by offering better products.</li> <li>❗ However, taking competitors' evaluation solely as a criterion to build SBCE IR has limitations to foster innovation. Often, innovative ideas might arise from internal or personal initiatives. Thus, improvement products better than competitors might lead designers to do only low level innovations just to beat competitors.</li> </ul>
	Will SBCE IR help to the quantity of ideas or concepts to generate ( <b>quantity</b> )?	<ul style="list-style-type: none"> <li>✔ Yes, SBCE IR creates more opportunities for designers to increase number of solutions because of specific problems given to them to overcome.</li> </ul>
	Will SBCE IR help to increase the quality of conceptual ideas to generate ( <b>quality</b> )?	<ul style="list-style-type: none"> <li>✔ Yes, if the customer requirements are well captured and evaluated in SBCE IR, it will help us to satisfy and also excite customers by overcoming contradictions. Moreover, the principles of SBCE increase the success of concepts to be feasible and to meet customers' expectations.</li> <li>❗ However, to improve quality of ideas, we need personal experience and ambitions of designers to explore concepts which can overcome contradictions.</li> </ul>
	Will SBCE IR help to identify novel ideas or concepts ( <b>novelty</b> )?	<ul style="list-style-type: none"> <li>✔ Yes, if we use TRIZ principles and tools, SBCE IR increases the chance of having novel ideas which might be out of the box.</li> <li>❗ However, to improve novelty of ideas, we need personal experience and ambitions of designers to overcome contradictions in SBCE process.</li> </ul>

	Will SBCE IR help to increase variety of concept to generate ( <b>variety</b> )?	<ul style="list-style-type: none"> <li>✔ Yes it creates variety in idea generated if it is supported by TRIZ principles and tools to overcoming contradictions.</li> </ul>
Simplicity/ Difficulties/ Scalability/Skills and capabilities needed for SBCE IR	Is building SBCE IR easy for a product?	<ul style="list-style-type: none"> <li>✔ Not difficult.</li> <li>❗ But time consuming, in terms of data collection.</li> <li>❗ Therefore, SBCE IR can be simplified by taking simpler version for small projects and full version for large projects.</li> <li>❗ Another way to simplify it will be apply it on modules or platforms that are shared by different products. In this way, it will be possible to share an SBCE IR by many projects and stabilize it (since customer requirements are stable for modules).</li> </ul>
	Is SBCE IR applicable to other products?	<ul style="list-style-type: none"> <li>✔ Yes, the SBCE IR is applicable irrespective of product types.</li> <li>❗ But it might be time consuming for big and complex products.</li> </ul>
	Can SBCE IR be applied for product platforms or modules?	<ul style="list-style-type: none"> <li>✔ Yes, is might be effective to apply SBCE IR at module levels that can be shared across products. This might reduce the time to construct SBCE IR and make it robust to changes in customer requirements and technologies.</li> </ul>
	What skills and capabilities are needed to use SBCE IR?	<ul style="list-style-type: none"> <li>❗ SBCE expertise, vision on the development process from customer requirement collection phase to the whole life-cycle of a product, TRIZ training, knowledge about customers and application areas where a product is used.</li> </ul>

## 2 INTRODUCTION TO PRODUCT DEVELOPMENT



The aim of this chapter is to introduce product development (PD) in general and to discuss the emergence of set based concurrent engineering (SBCE). SBCE is a paradigm where designers can utilize its core concepts to frontload designing processes with knowledge, and thereby design problems in early phase of design are addressed with higher fidelity and confidence. In this chapter, two problem solving approaches are identified: design-build-test and test-build-design. The former resembles the traditional approach to problem solving in PD (point based concurrent engineering, PBCE), where design decisions and commitments to a solution are made without having enough knowledge to do so. The latter resembles the concept of set based thinking, where decisions are postponed and broad set of options are pursued until enough data and knowledge are gathered to make informed decisions. This chapter illustrates the difference between these two problem solving approaches. Moreover, the rationale behind the potential advantages of SBCE compared with its opposite counterpart, point based concurrent engineering (PBCE), is discussed. In doing so, a review of the literature in this field has been carried out analyzing the publications dealing with PD and concurrent engineering. The initial approach to this study has been done to consider some key points related to the process of PD itself. Then, a review of concurrent engineering, information exchange and problem solving approaches in PD has been organized. Finally, a particular focus will be given to position SBCE in the context and evolution of concurrent engineering literature.

## 2.1 Introduction

In section 2.1, the definitions of PD are given. In section 2.2, problem solving approaches (design-build-test and test-build-design approaches) in early phase of design are discussed and compared. In sections 2.3 and 2.4, the traditional models of PD and the evolutions of concurrent engineering which are called point based serial engineering (PBSE) and point based concurrent engineering (PBCE) are defined and discussed. In section 2.5, the limits and risks of PBCE will be outlined. In section 2.6, SBCE is briefly reviewed to underscore its contributions to avoid the limits and risks of PBCE. Finally, in section 2.7, the conclusions of the chapter are presented by comparing PBCE and SBCE.

There are plethora of definitions that explain what product development means. Some of the definitions are listed below. It must be underlined, however, that PD is a process and the definitions selected are reflecting this aspect of its nature.

*“A business process can be described as “a number of interrelated activities needed to accomplish a specific task”  
(Garside 1998)*

*“Product development is defined as set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product” (Ulrich and Eppinger 2000)*

*“A new product development is an integral part of a healthy, growing economy and it contributes by generating revenue and profits to a corporation that otherwise would not have been generated” (Annacchino 2006)*

In general, PD process is defined as a set of activities involved in taking a design problem during PD from setting initial specifications to producing a finished artifact that meets specifications (Baldwin and Johnson 1996). It consists of numbers of decision-making activities that combine creative thinking, experience, intuition, and quantitative analysis, the characteristics of which are iterative, cooperative, evolutionary, and uncertain. These characteristics make the PD process complex. It involves thousands of decisions, sometimes over a period of years, with numerous interdependencies, and under a highly uncertain environment. A large number of participants are involved, such as architects, project managers, discipline engineers, service engineers, and market consultants. Each category of professionals has a different background, culture, and learning style (Formoso, et al. 1998). Trade-offs between multiple, competing design criteria must be made throughout the design process, often with inadequate information and under intense budget and schedule pressure. In particular, early design stages are extremely hard to evaluate and control against progress milestones due to the lack of physical deliverables such as drawings. It is difficult to measure the amount of work completed and remaining on any given task. Moreover, feedback from the production and building operation stage take long time to be obtained, and tends to be ineffective. To make matters worse, projects are increasingly subject to uncertainty because of the pace of technological change, the rapid shifting of

market opportunities, and the inability to keep pace with relentless pressure to reduce time and cost (Ballard and Koskela 1998).

In the literature, product development process is mostly depicted as linear due to the sequential structure of decision-making. I.e., the decision(s) taken at time  $t$  influence the set of decisions available at time  $t + 1$ . Regarding the specific course of actions contained in the development process, various authors list somewhat different generic product development processes, but they all share the same basic structure. The differences among them are given by the level of detail covered. One such generic development process is presented in Ulrich and Eppinger (2000) who list five major phases (see Figure 2.1).

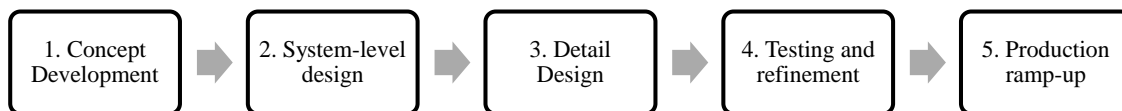


Figure 2.1: Generic phases of product development (Ulrich and Eppinger 2000).

The first phase (concept development) has the needs of the target market (i.e., the customer(s)) as a starting point. Then, one or more concepts are developed and tested. Ulrich and Eppinger (2000) define the concept as "a description of the form, function, and features of a product". The second phase (system-level design) is the first of two product design phases. It deals with the overall product architecture and engages in the definition of subsystems, their specifications, and the interfaces between them. The output of the second phase is a geometric layout of a product. The third phase (detail design) complements the previous phase in respect to the completeness of the overall design specifications. In this second product design phase the specifications of a product are developed to such a degree that production of all the unique parts can take place. The fourth phase (testing and refinement) is involved with constructing prototypes in order to test the developed product according to customer requirements and technical constraints. The fifth and final phase (production ramp-up) precedes the official product launch. This final phase marks simultaneously a major commitment by the production function and the official end of the development process.

## 2.2 Problem solving approaches in product development

Another view to understand PD is to consider it as a problem solving process. Thus it is useful to view the process as taking place in a "design space". Coyne et al. (1990) employ this concept with the purpose of creating a theoretical framework to discuss the process of improving an automobile design. Ward et al. (1995) state "for any given design problem, there is a true, yet unknown, 'design space' that includes all possible values for all the parameters."



An example of the design space is illustrated in Figure 2.2. It shows three sets of designs at different times  $t$ ,  $t+1$ , and  $t+2$  (all inside the true, yet unknown, design space). Each set represents the feasible designs, which the developing company is considering, at three successive points in time. At time  $t$  the company is contemplating the design A. The design characterizes a unique combination of design parameters, which is different in at least one parameter from other feasible designs. At time  $t+1$  the developing company has extended its search for an optimal design to include the design B. At the next point in time ( $t+2$ ) the design C is examined.

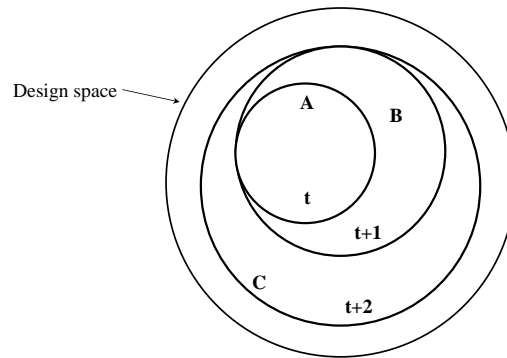


Figure 2.2: The design space representation (Sorensen 2006).

The goal for the developing company is to map out the various feasible designs in order to compare these to each other as there are combinations of design parameters, which are more optimal than others. Within the concept of the design space a development process becomes a problem-solving process of searching through a state space. "Problem" in this context is understood as a difference between the current state of the design and a more optimal design. A very important characteristic of this search process is the existence of uncertainty. I.e., it is not known with certainty (100%) what will be the outcome of the search process. There are two fundamental approaches to look for solution in the design space. The first one is called design-build-test and the second is test-build-design approaches.

### **2.2.1 Design – build – test approach**

The design-build-test cycle is based on an iterative view of design. It starts with fixing a given combination of design parameters and defining the values. The definitions of the values of the parameters are based on the experience or the information designers own (Kennedy and Harmon, 2008). Then, a prototype of the design is constructed, and finally is tested. Prototypes could be either physical or computer based (Wheelwright and Clark 1992). The outcome of the test is then compared to the objectives for the design. The test is to check if the design or the design parameters satisfy downstream or upstream constraints imposed to achieve internal and external integrity. However, if there is a discrepancy between the current design and the objectives,

management can opt to modify the design and start the cycle again to look for new solution or select a new solution from the design space (as seen in Figure 2.3). The result of this reiteration is that the design increases in detail after each cycle.

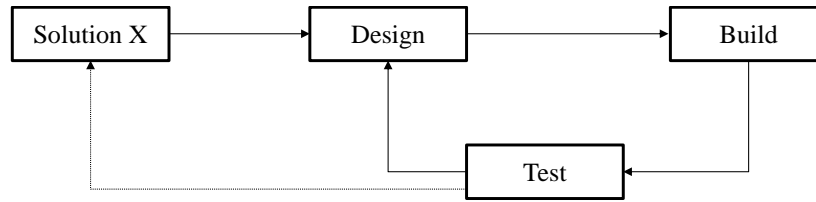


Figure 2.3: Schematic representation of a design – build – test approach.

Moreover, the number of alternative designs consider at the start here are very limited, usually one (Ward, et al. 1995). Designers consider in this approach a single solution they think could satisfy all the feasibility constraints. The number of solutions considered can be considered as discrete or range (Ward, et al. 1995, Sobek, et al. 1999). Discrete can be identified as countable solutions, for example, the possible material types. Ranges, on the other hand, can be identified as range of parametric values (Terwarch, et al. 2002).

### **2.2.2 Test – build – design approach**

This approach is the opposite of the former one. In this case, designers rather than fixing values for design parameters, they consider wider options in a design space as shown on Figure 2.4. That is, rather than committing on a single design parameter value or a single design option, designers postpone the decision until enough knowledge is gathered through testing range of options at the beginning. This approach, according to Sobek 1999 et al., is leaner compared to design and build approach. Since PD is characterized by uncertainty conditions, considering range of options will increase the success rate of design decisions (Ward et al. 2007). Moreover, it avoids expensive design changes once problems are revealed late in the process (Ward et al., 1995; Sobek, 1996; Kennedy and Harmon, 2008; Raudberget, 2010; Khan et al., 2011).

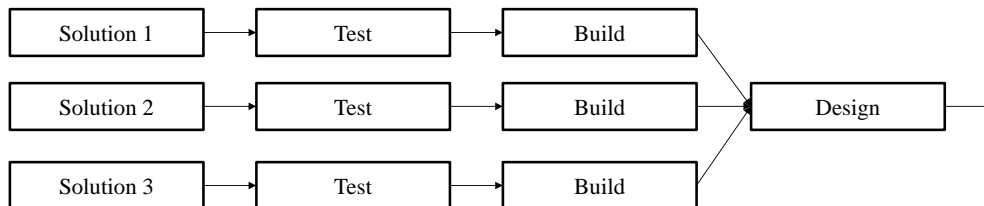


Figure 2.4: Schematic representation of a test – build – design approach.

This approach seems cumbersome at the beginning since designers have to test several solutions (or, make decisions as late as possible). However, after studying Toyota’s PD process, Ward et al. (1995) observed a paradox called ‘Second Toyota paradox’, where it considers alternative sub-system solutions and

aggressively evaluates them in parallel. Although, Toyota’s PD seems to be inefficient at the beginning, it showed to be the most efficient automaker in the world (Clark, et al. 1987; Clark and Fujimoto 1989; Womack, et al. 1990). In summary, the differences between the two problem solving approaches are presented in Table 2.1.

Table 2.1: Comparison between problem solving approaches in PD.

<b>Differences</b>	<b>design – build – test approach</b>	<b>test – build – design approach</b>
Search for solution	trial and error on a single point	experimentation of wider design space
Objective	satisfy requirements	satisfy requirements and create knowledge
Alternatives considered	one	multiple
Design decision	fast, based on incomplete information	delay decision, until proven information are gathered, and feasibilities are well understood
Advantages	fast and simple at the beginning of design	Innovation, knowledge building, avoid late design changes, the right quality at the right time
Risks	Weakens innovation, frequent design changes created by unpredictable events (increase costs and time of development)	Slow and difficult at the beginning of design

Keeping the differences of the problem solving approaches in mind, the following subsections discuss the evolution of concurrent engineering (CE) models. In general, there are three different CE models:

- Point based serial engineering (PBSE)
- Point based concurrent engineering (PBCE), and
- Set based concurrent engineering (SBCE)

## **2.3 Point Based Serial Engineering (PBSE)**

PBSE is the oldest and is characterized by the ‘functional’, ‘sequential’ and ‘over the wall’ model. The focus is on the functions (departments) that are responsible to carry out each stage of a design process. In this case, PD is a reactive process (Papalambros and Wilde 1991), the design teams naturally react to what is learnt in the previous step, or react to the decision that is made beforehand. In other words, it is not unusual that the results from one step drive the actions of the next step. From information exchange perspective, PBSE

represents a batch mode (Von Hippel 1995; Wheelwright and Clark 1992). The information or decisions that are made in upstream are communicated once finished. Design specifications are freeze as early as possible for other functions to start (Ward, et al. 1995).

Figure 2.5 shows a typical PBSE model in automotive development. In the process, styling starts by conceptualizing a design based on its criteria for optimality. It then sends the design "over the wall" to marketing, which then critiques the design based on its own criteria for optimality. The design is then sent back to styling, which iterates once again and adapts the design based on the marketing function's requirements. The design then passes on to body, which also comments on the design in the same fashion as marketing. Styling once again iterates and adapts the design to body's comments. In the same manner the design passes back and forth through chassis and manufacturing.

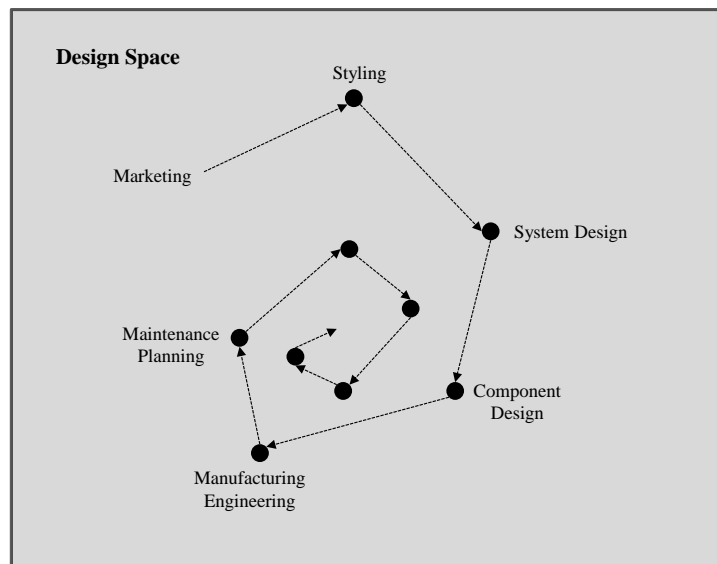


Figure 2.5: Problem solving approach in PBSE – an example from an automotive development (Ward et al. 1995).

From problem solving perspective, PBSE resembles the design-build-test approach as presented in Figure 2.3. In this approach, designers presume a single solution for their design problem at a time, and jump from a solution to another till time runs out (Kennedy and Harmon 2008). The strategy is characterized by a lack of information (on a pan-department level) between the participants in the development process. When presented with a design, each function goes through a design-build-test cycle based primarily on its own information set and criteria for optimality. The outcome forms the basis of a feedback loop, and the design is then updated (if needed). Because each feedback loop takes time, the result could be a lengthy problem-solving process. Moreover, there is no guarantee that designers converge into an optimal solution (Ward, et al. 1995; Sobek, et al. 1999). It is important to notice that the PBSE model assumes only one "main" design being developed. The feedback loops giving rise to a design change result in a changed design.

Several studies refute such models. PBSE causes different functions involved in the development to pass decisions once committed (Ward, et al. 1995). Such practice causes infeasibilities to be found late in the process which cause loopbacks/reworks (Alder 1995). Moreover, it leads to development delays, often associated with “omitting important considerations early in the design” (Anderson 1997). Unless a PD is functioning in a perfectly stable and precise environment, it is not practiced anymore in industrial context (Terwarch, et al. 2002).

Substantial amount of research and literature have been initiated to overcome the PBSE’s shortcomings. Researches and industrial practices created what currently known as ‘Concurrent Engineering (CE)’ (Eisenhardt and Tabrizi 1995; Krishnan, et al. 1997; Terwiesch, et al. 1997; Cusumano and Nobeoka 1998). The basic improvement is to bring more communication and increase the frequency of upstream and downstream information exchange. Moreover, the CE researches include design and process management capabilities for effective communication (Brown and Eisenhardt 1995). These capabilities are enablers that support PD managers to plan, schedule and control the flow of information in development process. In the following section, progresses in CE literature will be briefly assessed.

## **2.4 Point Based Concurrent Engineering (PBCE)**

The second type of PD process model is called point based concurrent engineering, PBCE (Sobek et al. 1999). This model is different from the PBSE in that communication between upstream and downstream partners will be intensified. Thus, from information exchange perspective it resembles the early involvement or integrated problem solving mode (Terwarch, et al. 2002). Concurrent Engineering (CE) has been increasingly popular in product development literature and practices (Simon 1969; Allen 1977; Wheelwright and Clark 1992; Eisenhardt and Tabrizi 1995; Iansiti 1995; Hauptman and Hirji 1996; Terwiesch, et al. 1997; Cusumano and Nobeoka 1998; Loch, et al. 2001). In general, CE can be evolved in terms of four perspectives (Smith 1997; Sapuana, et al. 2007): Integrative product team, Integrative mechanisms, task sequencing and gate reviews, requirement settings and release of information.

***Integrated product teams (IPTs) in PBCE:*** to facilitate CE, design organizations have moved away from the traditional functional configuration to adopt cross-functional design teams or integrated product teams (IPTs), illustrated in Figure 2.6. The primary aim of assembling such a cross-functional team is to enable a variety of perspectives to develop a product design concurrently, so that the final product is better integrated, and is developed more quickly and at a lower cost (Papalambros and Wilde 1991; Anderson 1997).

Womack and Jones further characterize cross-functionality in CE as one of the lean PD practices (Womack and Jones 2005). They note that an ideal design process would operate much like a single-piece flow in a

manufacturing system. Moreover, the IPTs enable to bring together individual knowledge required to develop design solution and facilitate effective and efficient information flow.

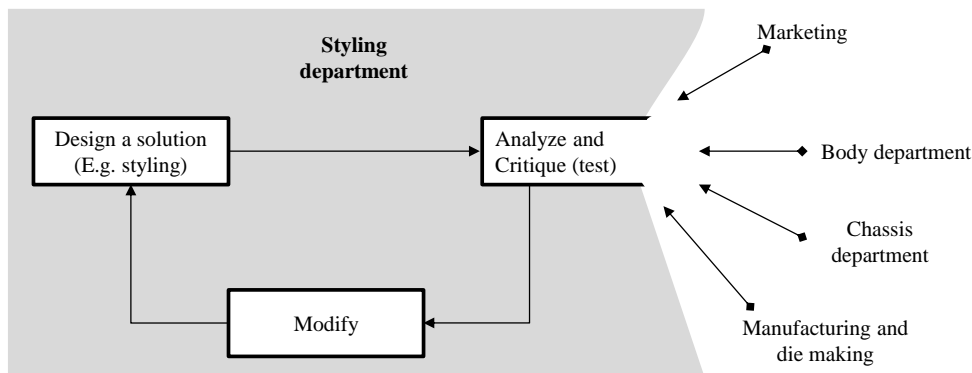


Figure 2.6: PBCE in automotive development (Sobek, et al. 1999).

**Integrative mechanisms (IMs) in PBCE:** Browning (1997) defines integrative mechanisms (IMs) as “strategies and tools for effectively coordinating actions between multiple” design organizations, such as integrated product teams (IPTs). Examples of IMs include information and communication technologies (such as linked CAD tools and common databases), co-location, face-to-face meetings, manager mediation, and interface contracts and scorecards (Browning 1997). Other CE tools such as Quality Function Deployment, QFD (Akao and Mazur 2003) and Failure Mode and Effect Analysis, FMEA (Dale and Shaw 1990) have been extensively used as mechanisms to facilitate communication between customer, designers and manufacturing process departments. These IMs are used to supplement the basic structure of the design team so as to further enhance the members’ abilities to share and combine their knowledge.

**Task sequencing and gate reviews in PBCE:** despite the effort placed on integrated problem solving, concurrent engineering, and the associated design tools and methods, many problems in engineering design are coupled; that is, one design group is dependent upon information from another group (Krishnan, et al. 1992). Such interdependent, chicken and egg problems are difficult to sort out, because it is “rarely possible to identify an unambiguous sequence for making decisions” (Chang, et al. 1994).

To cope with these coupled design problems, CE literatures resort to a sequential decision making strategy (Krishnan, et al. 1997). Such strategies require that a design problem must first be partitioned (decomposed) into a “number of sub-tasks that may then be distributed among a number of individuals (von Hippel 1990). Once a problem is partitioned, a tool such as a design structure matrix can be used to sequence the tasks to minimize the impact of iteration in the design (Browning 1996). By properly sequencing tasks, the costs of downstream changes to a design can be minimized (von Hippel, 1990). The drawback of such tools, however, is that while they might minimize the extent of the changes which need to be made during iteration, they may not help engineers determine the best sequence in which to make decisions (Krishnan, et al. 1991).

Associated with the sequencing of tasks or decomposing activities, CE brings strict control and gate reviews into a PD process. The formal reviews are to check the execution of activities before downstream activities begun. Product development models such as ‘stage and gate’ or ‘spiral models’ are typically designed to bring reviews and controls in CE environment (Cooper and Kleinschmidt 1993; Cooper, et al. 2002; Cooper and Edgett 2008).

***Requirement setting and release of information in PBCE:*** to cope with all of the difficulties associated with both integrating information across design groups and limiting the effects of iteration, conventional practice suggests that it is best to establish firm requirements early in the development process (Ward, et al. 1995). Requirements are finalized quickly to impose “as much constraint as possible in order to simplify the interactions among subsystems” and other members of a design team (Sobek, et al. 1997). The logic behind this approach is that since one design group does not necessarily know or understand the constraints faced by another group, each group must specify their subsystems in great detail to ensure their functionality and that they interface properly with other systems (Sobek, et al. 1999). This reliance, however, leads to two paradoxes.

The first paradox relates directly to the development of requirements. System design methods emphasize establishing requirements early, but iterative methods imply that the requirements will change over the course of successive iterations (Ward, 1990). The second paradox relates to the very reason for initiating a development effort. Reinertsen states that “the purpose of a design process is to generate information” Reinertsen (1997). An efficient design process, therefore, is one which generates information cost-effectively. When developing a design, the feasibility and appropriateness of the concept is determined through testing, so to be cost-effective, each test should generate as much information as possible. When conducting tests, more information is contained in the results of a failure than in the results of a success (Ward, et al. 2007). A design process, therefore, does not maximize the amount of information which it generates by maximizing test success rates, but by ensuring “an adequate failure rate to generate sufficient information” (Reinertsen, 1997). A philosophy of “do it right the first time” implies that a design would always successfully complete its development tests. Such outcomes, however, would not necessarily produce information in a cost-effective manner. The second paradox of iterative methods, therefore, is that a “do it right the first time” mentality actually decreases the cost-effectiveness of a design process by degrading the amount of information which the process produces.

These two paradoxes limit the efficiency and effectiveness of iterative design methods. While engineers and managers have developed many tools to aide in coping with these problems, current engineering methods do little to actually eliminate the sources of these paradoxes.

## 2.5 Limits and risks of PBCE

While IPTs (integrated product teams), IMs (integrative mechanisms), task sequencing, strict gate reviews, and early requirements definitions help to make CE approaches effective, PBCE still introduces the following additional risks:

- a) PBCE requires that downstream phases of design be able to operate using early upstream information (Krishnan, et al. 1996). Making use of such information entails risk because the information may not be finalized (Chang, et al. 1994; Krishnan, et al. 1996; Morgan and Liker 2006). When multiple views are involved in developing a new product, each group will recommend changes to a proposed solution to better reflect that group's constraints and requirements. This scheme of proposition and change, however, leads to several possible problems. Since each group in the design process does not necessarily understand the limits and needs of every other group, recommended changes can produce conflicts, leading to waste in the development process (Sobek, et al. 1999; Liker, et al. 1996). Moreover, work that could be conducted in parallel then reverts to a sequential pattern, and invalidates the true potentials of being concurrent (Liker, et al. 1996).
- b) There exist no guarantees that the iterative, point-to-point approach will ever converge on a final and optimal design solution (Sobek, et al. 1995). Instead, the iterative loops are never quite closed, and, in the worst case, "problems are resolved when production begins, by selecting whatever last minute compromise is easiest" and when the cost of making changes become high (Ward 1990).
- c) Strict controls at gate reviews in PBCE not effective in mitigating the underlying problems in design (Morgan and Liker 2006; Ward, et al. 2007). As discussed above, when a design is complex and sub-systems are coupled, anticipating the possible failures of the design becomes very difficult. In addition, models such as 'stage-gate' are based the controls on unrealistic millstones that would completely change through a given time of a design stage. Therefore, the gate review evaluate designers and design projects based on wrong interpretation of the nature of PD, without understanding the unpredictability of design science and philosophy (Ward, et al. 2007).
- d) Finally, the problem solving approach is PBCE resembles the design-build-test approach. As described above, designers in this paradigm consider only single solution for their problem. These have two negative effects in CE approach. The first one is that, since enough exploration of a design space are not explored at early phase of design; iteration and rework become evident (Kennedy and Harmon 2008). The second one is that, design is not only a process of developing product but it is also a process of manufacturing knowledge about design problems (Ward, et al. 1995). Therefore, following PBCE limits the design organization's potential to build knowledge and learning.



From the above discussion it is clear that both PBSE and PBCE pose limits to the efficiency and effectiveness of PD. In the next section, the next evolution of CE called set based concurrent engineering (SBCE) will be presented briefly. Late in chapter 3, SBCE's definition and principles will be discussed. Moreover in this thesis, an extensive literature review is made in chapter 4 to define the enablers needed to execute SBCE's principles.

## 2.6 Set Based Concurrent Engineering (SBCE) in brief

Allen Ward and his colleagues are the original proponents of SBCE who studied Toyota's development process for several years, conducting detail interviews and making observations. They have observed that Toyota's PD is significantly different than most of US automakers (Ward, et al. 1995). The difference is that most of US automakers tend to make decision very early in design (e.g. specification freezing of body style). This practice is similar to what has already been discussed as PBCE. But Toyota, rather than early commitment, it practices delaying of decision until enough knowledge and data are obtained. While delaying decision, designers explore and test several alternative sets in parallel to obtain enough knowledge about the performances of the sets. Test results are presented in the form of trade-off curves, limit-curves, checklists and standards (Ward, et al. 1995; Sobek, et al. 1999). These forms are paramount in Toyota's PD to easily capture, share and reused knowledge across design teams effectively. Moreover, they facilitate to make the right decision based on data (Ward, et al. 2007; Oostewal 2010).

After looking these results, the proponents of SBCE call this paradigm "The Second Toyota Paradox" (Ward, et al. 1995). While the first paradox is how lean production seems highly inefficient compared to mass production paradigm, the second paradox is how set based thinking (delaying key decision and exploring multiple solutions in parallel) seems inefficient compared to point based paradigm, though it is not (Ward, et al. 1995). Researcher reported the superior Toyota's performances compared to both European and US automakers in the late 80's and the beginning of 90's (see Table 2.2).

In order to understand the leverages of SBCE compared to PBCE, it is useful to observe how design process behaves from three different perspectives: (a) evolution of product cost, (b) management's influence to affect product cost, and (c) the evolution of designers' knowledge about a design problem.

- a) **The evolution of product cost:** designers will make decisions affecting the life-cycle of the product. As shown in Figure 2.7, the incurred cost at early phase of design which is spent in design activities is very small. However, more than 60% of a product's life-cycle costs (e.g. manufacturing costs, maintenance costs, etc.) are defined or committed in early conceptual stages (Terwiesch, et al. 2002; Anderson 1997). In addition, these stages are subject to uncertainties and the knowledge available to designers to make the

right decision is limited (Terwiesch, et al. 2002; Anderson 1997). Thus, the idea of delaying decisions, exploring multiple solutions and investing more to gain knowledge about feasibilities and compatibilities make SBCE much more sensible than PBCE (Ward, et al. 1995).

Table 2.2: Comparison of PD performances of Toyota and other automakers (Clark, et al. 1987; Clark and Fujimoto 1989; Womack, et al. 1990).

Measures in average	Toyota	North American	European
Engineering efforts for a new vehicle (million hrs.)	1.7	3.1	2.9
Development time (months)	46.2	60.4	57.3
Engineering change cost (% total cost)	10-20%	30-50%	10-30%
Employees per team	485	903	904
Ratio of delayed project	1 in 6	1 in 2	1 in 3
Achieve normal quality after launch (months)	1.4	11	12

- b) **Management’s influence to affect product cost:** the problem of making right decisions at early phase of design becomes even more evident when one considers management’s ability to influence a design if failed to pass constraints late in the process. Management can exert its greatest influence on a product early in the development cycle. As the cycle progresses, however, this power is greatly diminished (Wheelwright and Clark 1992). In addition, the costs associated with making any changes to a product design rise exponentially late in the process (Krishnan, et al. 1991; Reinertsen 1997; Anderson 1997). In PBCE, designers tend to take only a single alternative solution early in the beginning (Sobek, et al. 1999). This limits the flexibility of making changes once problems are revealed late in the process. Moreover, since alternative solutions are not explored and their performances are not taken into account, designers are not capable to fix design problems without delaying projects and missing market opportunities (Oostewal 2010).
- c) **Evolution of designers’ knowledge:** another most important factor which is closely related to the other is the evolution of knowledge of designers (Bernstein 1999; Reinertsen 1997). This means that, there are several changes that might occur during the development process once a project is started. For example, customers might change what they ask, or previously unknown constraints from testing might emerge (Oostewal 2010). Therefore, designers’ knowledge about the requirements from different stakeholders is not fully known at the beginning. As designers work on a design problem and become familiar with the product concept they increase their understanding. However, there is inherent design paradox as clearly

seen here. Whenever the designer or managers have more chance to make changes, there is a lack of knowledge about the specific problem. But, the more knowledge gained about the problem it will be already late to make changes unless sacrificing time to market or incurring additional costs. Moreover, in many industries knowledge gained in a previous project is not effectively reused to avoid mistakes in future projects (Kennedy and Harmon 2008; von Hippel and Tyre 1994). Therefore, the SBCE's concepts of considering sets of alternatives, conducting tests and simulations before commitment, and effectively managing the transfer of knowledge from projects to projects enable developers to access knowledge during early phases of design to make the right decisions. As a result, SBCE is a much more sensible approach to PD than PBCE.

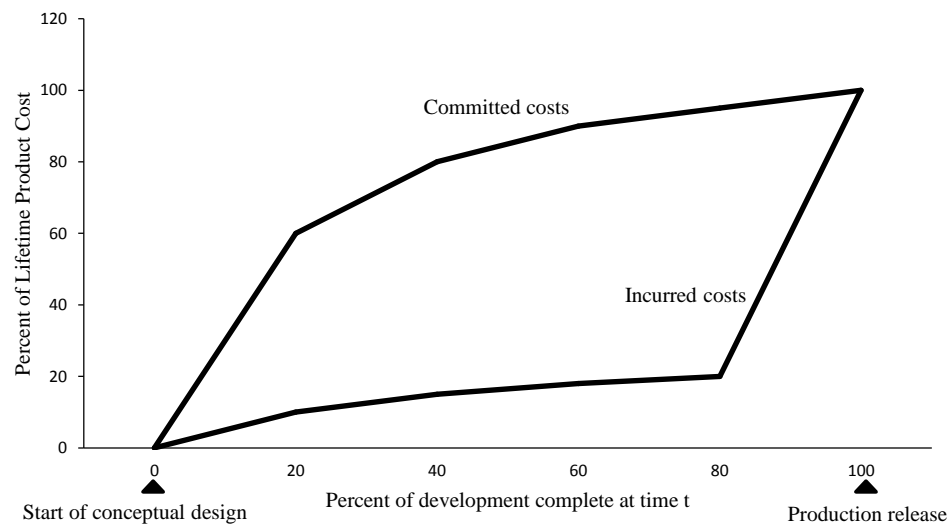


Figure 2.7: Committed cost and incurred cost as a design process progresses (Anderson 1997).

## 2.7 Conclusions

In summary, CE has evolved to improve communication and increase the quality of decision making between upstream and downstream design activities. However, the point based approach to design process limits its effectiveness. Since the nature of information in design and product development process is unpredictable, following PBCE causes rework, incurring additional cost and missing market opportunities.

Moreover, PBCE is based on a design-build-test paradigm of problem solving; designers are not exploring possible design alternatives in such paradigm. Thus, it limits the flexibility toward unexpected change late the process. As a consequence, designers cannot identify, capture, use and reuse design knowledge in a project or across projects through exploring and testing multiple design solutions. Therefore, there is a need for a paradigm shift whereby flexibility towards late design changes is effectively avoided. SBCE offers such a paradigm shift. The comparisons between of PBCE and SBCE are summarized in Table 2.3.

Table 2.3: Comparison of PBCE and SBCE<sup>6</sup>.

Areas	PBCE	SBCE
How conceptual solutions are found?	Iterating on existing concepts	Defining feasible regions
Which design concept is communicated?	The “best idea or best guess”	Sets of possibilities
How should a system be integrated?	Pass a concept idea among teams for critiques	Look for feasible intersections
How should a design be optimised?	Define, analyse, test and then design till objectives are met	Build prototypes in parallel, tests and define feasibilities and workable solutions
How specifications are managed?	Maximising constraints to assure functionality goals and interface fit	Using minimum constraints to allow mutual adjustments among functional teams
How design risks are managed?	<ul style="list-style-type: none"> <li>• Establish feedback channels</li> <li>• Communicate often</li> <li>• Respond quickly to changes</li> </ul>	<ul style="list-style-type: none"> <li>• Establish feasibilities before commitment</li> <li>• Pursue high risks and conservative conceptual solutions in parallel</li> <li>• Seek for robust solution to physical, market and design variations</li> </ul>
What are the theoretical advantages?	<ul style="list-style-type: none"> <li>• Simple</li> <li>• Fast at the beginning of a process</li> <li>• Applicable to predictable process</li> </ul>	<ul style="list-style-type: none"> <li>• Increase flexibility in early phase of design</li> <li>• Improve knowledge and learning</li> <li>• Reduce risk of late changes and reworks</li> </ul>
What are the theoretical limitations?	<ul style="list-style-type: none"> <li>• Low flexibility to make changes</li> <li>• High risk of reworks</li> <li>• Low level of knowledge creation and reuse</li> <li>• Low level innovation</li> </ul>	<ul style="list-style-type: none"> <li>• Extensive and expensive</li> <li>• Difficult to implement</li> <li>• Requires higher leadership quality and capabilities (enablers)</li> </ul>

In chapter 3, the definition and principles SBCE are explained in more details. SBCE is a process which is composed of its own principles. The principles are guidelines that offer unique ways to develop new products. Moreover, similar existing approach that resembles SBCE are analysed in this chapter.

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<sup>6</sup> Compiled from: Ward, et al. 95; Sobek, et al. 99; Ward, et al. 07; Kennedy and Harmon 08; Oostewal 10; Raudberg 10.

In chapter 4, a comprehensive literature review is made to comprehend the key enablers (strategies and capabilities) that are necessary that are needed to execute the principles. Without the enablers mentioned in chapter 4, SBCE cannot achieve the desired paradigm shifts posed in Table 2.3 and industries won't able to benefit from its potentials.

### 3 SET BASED CONCURRENT ENGINEERING IN CONTEXT



The aim of this chapter is to put SBCE in context in terms of its definition and principles. The strength and uniqueness of SBCE lies in its definition and principles. The general principles of SBCE can be summarized as: principle of exploration, principle of set based communication and principle of convergence. From the principles, it can be observed that SBCE follows a funnel process where alternative concept are explored, communicated and evaluated for convergence. These principles are derived from Toyota's PD. Nonetheless, some of the principles are already been addressed by exiting literatures in PD. What makes SBCE's principles different is the way the funnel process is execute. The principles dictate the use of proven knowledge to explore, communicate and converge sets. Moreover, these principles are supported by simple tools and mechanisms to facilitate knowledge identification, capturing and representation. This chapter therefore reviews the definitions and principles of SBCE. Furthermore, in this chapter, the differences and similarities of SBCE with seemingly similar approaches are also investigated to underscore its unique features.

## 3.1 Introduction

This section is dedicated for introducing the details of SBCE in terms of its definition and associated principles. From sections 3.1.1 to 3.1.4 the principles are elaborated and discussed in more details. These principles are taken from already existing literature on SBCE. In section 3.2, similar existing models or approaches that are seemingly similar to SBCE are assessed and contrasted in this section.

### 3.1.1 SBCE definition and principles

Sobek (1997) summarizes the definition of SBCE as engineers and product designers “*reasoning, developing, and communicating about sets of solutions in parallel and relatively independent*”.

This definition can be well understood by analyzing it one piece at a time. The first component of SBCE is to develop sets of designs, i.e., multiple design alternatives, for a given design problem. Rather than trying to identify one solution, engineers should instead develop a variety of design options, and then gradually eliminate alternatives, until only one option remains. However, sets here could be discrete solutions (for example, the material of an airplane structure could be an aluminum or carbon composite materials). Sets could also be a range of values for a parameter (for example, the area of an airplane wing structure could take a range value (X to Y)).

The second component reflected by the definition is the involvement of teams from different sub-system functions. Each subsystem functions should explore its own sets of solutions independently to others taking their own perspective. Then, the sub-system teams progressively interact to compare the sets, looking for regions of overlap. The teams then aggressively converge into a solution which satisfies the constraints from all other perspectives. Independent exploration of design sets enables several engineering specialties to consider a design problem from their own perspective (i.e., to allow each specialty to work on a sub-problem) and then to effectively re-combine those independent alternatives into an integrated final solution (Bernstein 1998).

The third component is more subtle and unique part of SBCE than the other two components. The word ‘reasoning’ indicates that designers should explore solutions, communicate their feasibilities, and converge to a preferred solution using data and knowledge. This concept has not been understood well in many of the works after Sobek et al. (1999). Latter, once the concept of SBCE is put into real industries its significance becomes clearer (Ward, et al. 2007; Oostewal 2010). As Allen Ward wrote in his dairy that “one thing I learned about Toyota’s development is their extensive use of trade-off and limit curves” (Ward, et al. 2007). It seems as if the languages of engineers in Toyota are based on trade-off and limit curves. As one engineer in Toyota reported “we have built as many as 10 to 20 exhaust systems for every project because the chief

engineer wants to know what the trade-offs are” (Ward et al. 2007). However, Toyota uses these curves not only to explore and converge to solutions but also to capture and document knowledge effectively (Kennedy and Harmon 2008).

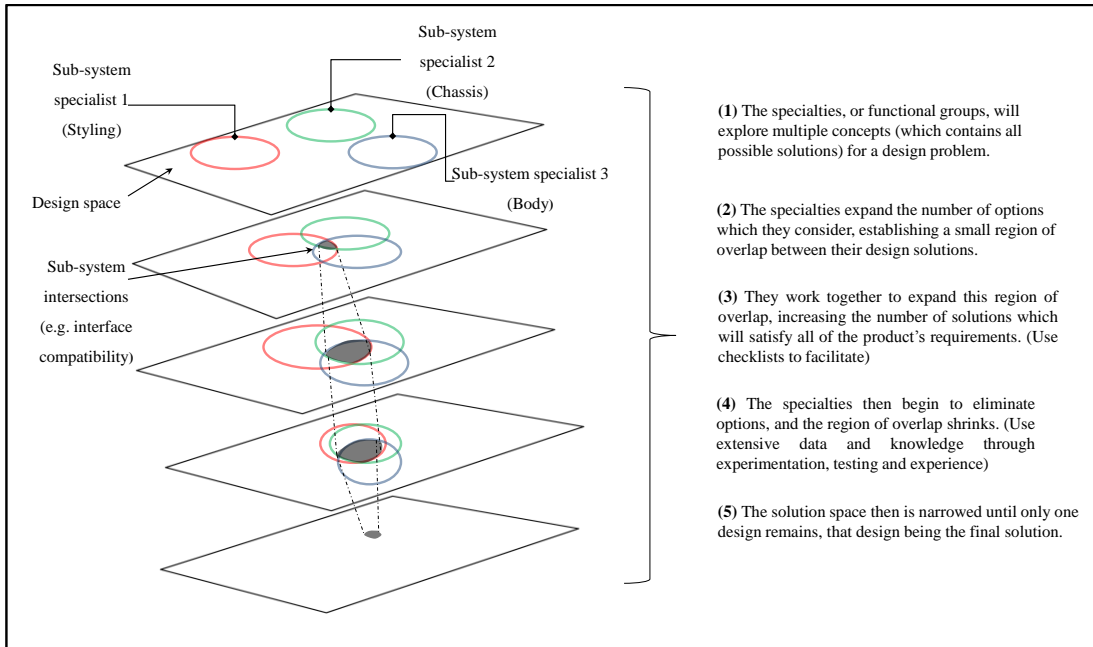


Figure 3.1: Conceptual schema of SBCE (Bernstein 1998).

Figure 3.1 summarizes the definition of SBCE in its simplest form. As it can be seen, SBCE starts with designers exploring the design space to develop alternative conceptual solutions for a problem. Then, sub-system designers will extensively communicate to look for intersection or overlaps. Each sub-system function is responsible will analyses the governing tradeoffs to evaluate solutions (Sobek, et al. 1999). Limit-curves are also used to understand the technical feasibilities of solutions. Using limit curves designers are able to eliminate solutions which are proven to be inferior. Unless a concept solution is proven inferior, it will be kept inside the candidates set (ward, et al. 1995; Sobek, et al. 1999).

SBCE has principles and key features which are derived from Toyota’s PD, these principles are general guidelines. Sobek et al. outlined what designers should follow while developing products in SBCE approaches (Sobek, et al. 1999). In the following sub-sections of the chapter, the principles are discussed adding more rationale to support the principles from other literatures. The discussions of the SBCE principles are organized as follows:

- Principles of exploration (or, *Map the design space*)
  - Defining feasible regions
  - Explore tradeoffs by developing sets



- Communicate set of possibilities
- Principles of set based communication (or, *Integrate by intersection*)
  - Looking for intersection of feasible sets
  - Impose minimum constraints
  - Seek conceptual robustness
- Principles of convergence (or, *Establish feasibility before commitment*)
  - Narrow sets gradually while increasing details
  - Stay within sets once committed
  - Control by managing uncertainty at process gates

### **3.1.2 Principle of exploration**

The first principle of SBCE is to “*Map the design space*”. Toyota applies this principle on two levels (Sobek, et al. 1999).

First, on individual projects, Toyota engineers and designers explore and communicate many alternatives. The exploration, analysis, and communication help the development team “map out” the possibilities, along with associated feasibilities and relative benefits or costs, for systems and subsystems pertaining to the vehicle and its production. The goal is a thorough understanding of the set of design possibilities that apply to the problem, or what design theorists call the “design space” (Coyne, et al. 1990). This can be based on their experience, analysis, experimentation and outside information and so on (Sobek, et al. 1999).

Second, the principle applies on an ongoing basis when engineers capture what they have learned from each project by documenting alternatives, trade-offs, and technical design standards (Sobek, et al. 1999). This is what latter called dynamic knowledge capturing (Enberg, et al. 2006). In their study, Enberg et al. (2006) found that, knowledge is dispersed within development teams. And, it is difficult to identify knowledge which is intrinsically embedded to once mind (tacit knowledge).

This principle is consistent with research results about Japanese development structure. A key learning tool in Japanese organizations is decentralized groups studying, standardizing, and documenting processes and designs, then making the documentation publicly available to team members. Engineering checklists are also consistent with observations of numerous researchers on organizational learning in Japanese companies (Funk 1993; Nobeoka and Cusumano 1995; Nonaka and Takeuchi 1995; Verworn, et al. 2008). Therefore, in PD, Toyota’s SBCE practice reveals that, it is not just an exercise of exploring the risks and potentials of design alternatives. But also, visualize and documenting the knowledge obtained by testing and communicating alternative solutions. Understanding and documenting technical knowledge in the forms of trade-off curves, checklist and limit cures transfer tacit to explicit knowledge (Davenport, et al. 1998). Thus,

visualizing of technical knowledge determines the success of development projects (Ward, et al. 2006; Whyte, et al. 2008; Oostewal 2010).

### **3.1.3 Principle of set based communication**

The second principle is concerned with how to communicate the sets among teams to achieve system integration and find solutions which are workable to all functions (Sobek, et al. 1999). This principle is very crucial to optimize the system (full system). If engineers develop alternative sub-system solutions rather than one, there is a higher probability that the complete system works and achieves higher total system performance (Ward, et al. 2007; Sobek, et al. 1999; Black and Mendenhall 1993; Pugh 1990).

This principle contains three sub-principles: *looking for intersection of feasible sets*, *impose minimum constraints* and *seek conceptual robustness* (Sobek, et al. 1999).

The principle of *looking for intersection* basically amplifies the set based thinking in PD. Once designers have range of alternatives, they need to look for intersection areas. Communication based on sets or ranges of values facilitate coordination between upstream and downstream functions. Krishnan et al. (1992) noted that the decisions made by the various functional decision makers are generally coupled and often in conflict, and consequently wreaked cross-functional teams to perform worse than fully integrated teams. Therefore, communication between functional groups must not only build and transfer design knowledge, it must also help to coordinate the groups. Such early communication of performances is crucial to avoid rework late in the process. Hauptman and Hirji (1996) found in their study that, communicating performance information early entails risks of errors and frustration. The danger arises from the nature of information in design which is normally subject to changes and imprecision (Schrader, et al. 1993; Pitch, et al. 2002). In SBCE, team members communicate information they actually possess rather than sharply defined as practiced in PBCE (Liker, et al. 1996).

The principle of *imposing minimum constraints* is related to the fact that communication in SBCE is based on rough and range of values rather than single choice. Chang et al. (1994) noted that, engineers need to provide feedback to the designers of neighboring components about their preferred values for connecting variables and the cost of deviation from those values. Rather than only communicating a single design concept, engineers using set-based practices communicating about several. This set then provides information about the limits and boundaries faced by each group, allowing designers to better understand what decisions they can make to accommodate the needs of other engineers. Further, Liker et al. (1996) stated that when communicating between functional groups early in the design process, partial information is most useful if it involves boundaries on parameters. Such bounding information is exactly the type of knowledge contained

within a set. See Figure 3.2 that shows how Toyota communicates with its supplier based on rough and early specification (set based communication).

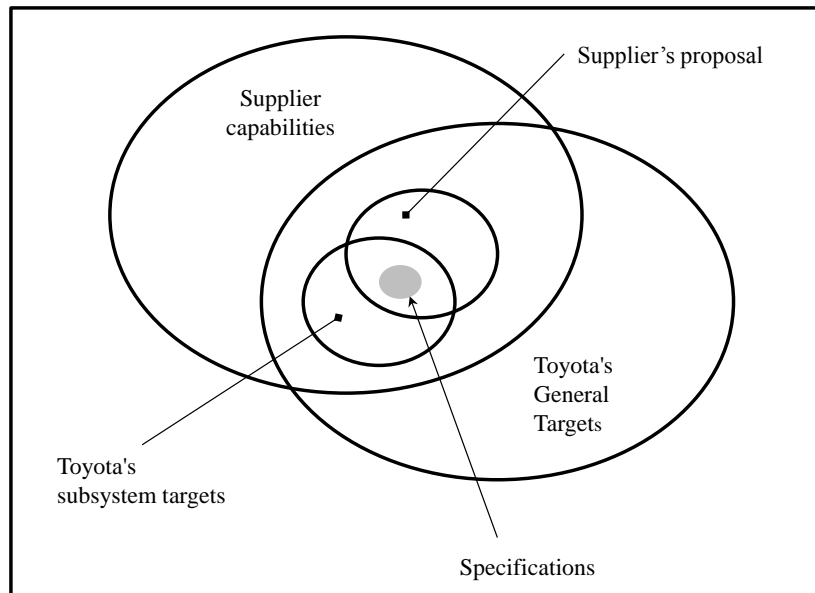


Figure 3.2: Intersections of possibilities help define specifications between Toyota and its suppliers (Sobek, et al. 1996).

Another principle which belongs to set based communication is that of *conceptual robustness*. This concept is based on Taguchi's notion of functional robustness. Taguchi states that a product is functionally robust "if it inherently tends to diminish the effect of input variation on performance" (Bryne and Taguchi 1986; Taguchi 1988; Taguchi, et al. 2000). Similarly, design decisions are conceptually robust if the decisions remain valid regardless of the choices made by other engineers working on the product (Sobek, et al. 1999; Chang, et al. 1994). As engineers narrow their sets and communicate about their remaining alternatives, they should also seek to make future choices that will accommodate as many of the other engineers' options as possible. When engineers are able to follow this principle, they significantly reduce the likelihood of having to redo their work because of decisions made by other designers.

### **3.1.4 Principle of convergence**

Rather than picking one solution early in a design process (as in point based approach), SBCE is a process of elimination of inferior designs and the development of feasible ones. However, Allen Ward called the Toyota's elimination process as aggressive (Ward, et al. 2006). This is because, although there is frequent communication between sub-system teams, in a complex system there could be very large sets at the beginning. Therefore, systematic and aggressive elimination of inferior designs are necessary. The

convergence process demands design participants (either internal and suppliers) to make their set narrowed in parallel.

An important principle to which to adhere during this process is that of *establishing feasibility before commitment* (Sobek et al., 1996). Before committing to keep a certain design concept, engineers must ensure that, at the current level of detail, the design is in fact feasible, i.e., that it does meet the product's requirements. The goal of this principle is to avoid uncovering problems late in the design process. Note, however, that the intent is not to necessarily test every concept to the highest level of detail possible. On the contrary, designs should only be tested to the level of detail appropriate to the size of the set. If the set is large, implying that the product is still early in its development, tests should be simple and quick, just detailed enough to expose problems that are near the surface (Parunak, et al. 1997).

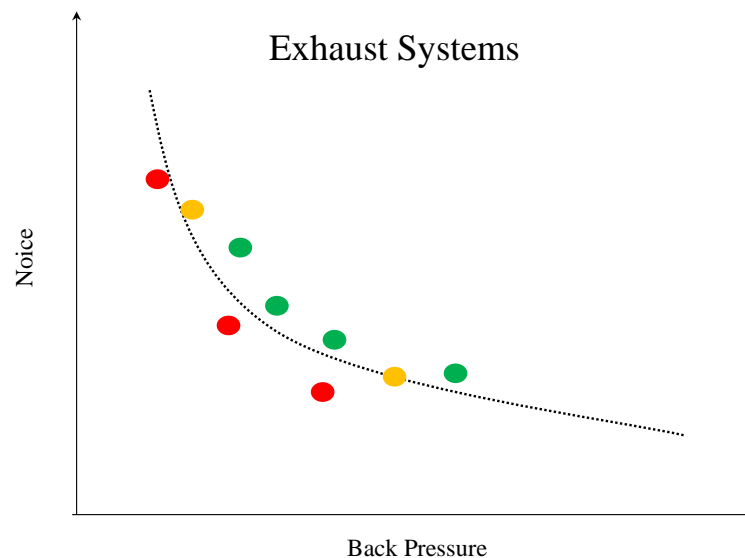


Figure 3.3: Trade-off curve for Exhaust System in Toyota (Ward, et al. 2007).

The principle of *narrowing set of alternatives gradually* is another central essence of SBCE process. Gradual elimination indicates that engineers need to check feasibilities of sets of solutions through testing and communication (Sobek, et al. 1999). It is different from point based thinking in that, in set based thinking sets are eliminated rather than selected. Unless there are data showing a solution is infeasible it will stay with sets. There are mechanisms that facilitate this process such as tradeoff and limit-curves (see Figure 3.3 as an example of trade-off curve used to evaluate alternative exhaust systems).

Once engineers have narrowed a set, it is important that one engineer not “jump out” of the set to introduce a new design concept, unless absolutely necessary. This is the principle of *stay once committed*. This commitment is essential so that other engineers can rely on each other's communication (Sobek et al., 1999).

In many ways, therefore, these concepts illustrate a key notion that in SBCE designs converge rather than evolve (Liker et al., 1996).

The final principle included in convergence is *managing uncertainties at process gates*. This principle dictates that, in SBCE managers must be sure that convergence really occurs. However, supervising these convergence processes for both designs and requirements mandates a slightly different management approach than is normally used in engineering design (Sobek, et al. 1999). In PBCE, completion of design activities are controlled by gate controls (Cooper and Kleinschmidt 1993; Cooper, et al. 2002; Cooper and Edgett 2008). Traditional phase gate methodology promotes progression of product development linearly through distinct phases (stages) of development (Oostewal 2010). However, in SBCE, gates are substituted with integration events (Ward, et al. 1995). Integration events, as opposed to design reviews or checkpoints, are points where multiple functions show their design performances and receive feedback from other system or chief engineers (Oostewal 2010).

## 3.2 Comparison of SBCE with similar approaches

Many authors on design and engineering field emphasize the importance of considering multiple design alternatives, especially early in the design process. For example, Pahl and Beitz (1988) stated that the solution field should be as wide as possible at the start. Ulrich and Eppinger (2000) cited several common failures in concept development which stem from not evaluating enough design options, including: only considering one or two alternatives, failing to consider concepts used by other firms in related or unrelated products, failing to successfully integrate several promising “partial solutions” and failing to consider “entire categories of solutions”. In addition, they noted that, through exploration of alternatives in the development process there are more chances to develop best performing options. There are four prominent approaches in which the consideration of alternative is deemed important: *Pugh’s controlled convergence* (Pugh 1990), *fast Design-Build-Test cycle* (Wheelwright and Clark 1992), *spiral development* (Boehm 1986) and *platform design* (Meyer and Utterbeck 1993).

- **Pugh’s controlled convergence**

Pugh recommends a method of “controlled convergence” (Pugh 1990). In this approach to design, engineers and designers initially develop a very large number of design concepts. These concepts are then compared to the customer’s needs and to one another. Concepts which rate highly are retained, while others are discarded. Once the initial number of designs has been reduced, the design team again considers additional alternatives either modifications of some of the initial concepts or entirely new concepts. This set of designs is narrowed further, and then, again, new options are added. The process continues in this fashion, with the generation of

ideas followed by convergence. Each successive iteration of the process results in a narrower and narrower field of alternatives, until only one option remains.

- **Design-Build-Test cycle and Spiral development**

Wheelwright and Clark proposed a similar approach to design based upon the design-build-test cycle. The first step in the process is to frame the problem: establish product and manufacturing process requirements, clarify user needs, etc. Once the requirements are clearly understood, several alternative designs are developed, the purpose of which “may be to explore the relationship between design parameters and specific customer attributes” (Wheelwright and Clark 1992).

Models, either physical or computer-based, are then constructed and “subjected to tests that simulate product use” (Wheelwright and Clark 1992). If the models fall short of performance requirements, “engineers search for design changes that will close the gap” between the models’ performance and the required performance (Wheelwright and Clark 1992). The design-build-test cycle is then repeated, until all of the requirements are fulfilled. This approach to design, therefore, is built around the concept of repetition. A single design-build-test cycle is used to provide information to the next iteration of the cycle. The effectiveness of this method, then, depends upon the effectiveness of a single cycle, the number of cycles that are completed, and how well the results of individual cycles are combined into coherent solutions. Perhaps this method raised into acceptance due to the emergence of computer aided simulation and prototyping techniques in the manufacturing domain (Thomke 1998; Thomke, et al. 1998). Note that, the design-build-test approaches resembles set based thinking if the consideration of alternatives considers are for learning and closing knowledge gaps about design problems (Bernstein 1998).

Similar to the Design-Build-Test cycle is the spiral approach which is prevalent in software development (Boehm 1986). The spiral model combines the idea of iterative development (prototyping) with the systematic, controlled aspects of the waterfall model (Larman and Basili 2003; Al-Ashaab, et al. 2009). It allows for incremental releases of the product, or incremental refinement through each time around the spiral. The spiral model also explicitly includes risk management within software development. Identifying major risks, both technical and managerial, and determining how to lessen the risk helps keep the software development process under control (NASA 2004). This approach uses many of the same phases as the waterfall model, in essentially the same order, separated by planning, risk assessment, and the building of prototypes and simulations (Boehm 1986).

Comparing the above two similar approaches (controlled convergence and design-build and test cycle) and SBCE, all recommend pursuing multiple alternatives. However, there are some difference with respect to how the options are used (Bernstein 1998). In both Pugh’s controlled convergence method and

Wheelwright's and Clark's design-build-test cycle, alternatives are generated to understand how different design parameters impact a concept's ability to satisfy a user's requirements. SBCE uses design options in this manner, but also use options to allow each specialty group working on a product to explore the design space independently. By allowing specialty groups to independently analyze their design options, SBCE eliminates the iterative paths which can be so problematic. Controlled convergence and design-build-test do not necessarily emphasize this use of design options. Moreover, the design-build cycle uses tests to determine whether or not to consider new design options, while SBCE uses tests to eliminate previously determined options to increase the level of detail in remaining design alternatives and generate knowledge (Bernstein 1998). The drawback of SBCE is that, it starts with all alternative designs available in a design space, which in practice, seems very difficult to attain. In this case, the design-build-test cycle (which starts from few alternatives and provide a mean to expand options), can be used along SBCE process (Bernstein 1998). However, as it will be in chapter 4, there are technological advancements that can map out possible solutions designers can take into account in SBCE (Ross and Diller 2004; Ross and Hasting 2005).

- **Platform design**

Platform design refers to a product development strategy in which a company develops a family of products which can share components and assets to target specific market segments (Meyer and Utterbeck 1993; Jiao and Tseng 2000; Krishnan and Ulrich 2001). A product platform, therefore, consists of the design and components which are shared by a set of products. By combining components in different combinations, a platform can give rise to variant of different products addressing different market needs. Platform design, therefore, is refers to product strategy of developing a product families. However, SBCE is a design strategy used to implement a product strategy (Bernstein 1998). So, SBCE can be used to design a product platform. However, as some research recommended, platforms and modular designs facilitate the SBCE process (Morgan and Liker 2006; Hoppmann 2009). It supports designers to focus their SBCE efforts only on a system area where exploration and testing are needed. If part of a system can be standardized and modularized in the form of platforms, SBCE efforts become more effective to drive innovation in product to serve a market.

### **3.3 Conclusions**

In conclusion, SBCE involves three basic principles such as exploration, set based communication and convergence. The principles are derived from evidence from automotive development practice in particular from Toyota's PD. The principles however are very sensible to be adapted to other product types and also industries. The general objective of the principles is to make PD a lean process and to create a knowledge based environment in design practice through mechanism suggested (tradeoff curves, checklist, and

standards). In particular the benefits of SBCE’s principles are: to arrive to an optimal design concept that maximizes value for customers and companies; reduces expensive reworks late in the process that eventually result in delay and budget overruns; improve innovation potentials by exploring enough alternatives at the start when there is more flexibility to do so.

Table 3.1: Comparison of SBCE with similar approaches<sup>7</sup>

Approaches	Similarity	Differences
Pugh’s controlled convergence	<ul style="list-style-type: none"> <li>• Consideration of large number of solutions</li> <li>• Elimination of inferior solutions rather than selection</li> </ul>	<ul style="list-style-type: none"> <li>• Solution space converge and diverge at any time in the process, rather than convergence in SBCE</li> <li>• Not necessarily involves SBCE principles</li> <li>• Not necessarily dictates parallel development of concepts</li> <li>• Not necessarily involves mechanisms to facilitate SBCE’s principles</li> <li>• Not necessarily focuses on knowledge based paradigm<sup>8</sup></li> </ul>
Design-Build-Test cycle and Spiral development	<ul style="list-style-type: none"> <li>• Considerations of multiple solutions</li> <li>• Fast feedback for teams</li> </ul>	<ul style="list-style-type: none"> <li>• Small number of solutions</li> <li>• Fact cycle based on several design modifications, rather than parallel development and convergence as in SBCE</li> <li>• Not necessarily involves SBCE principles</li> <li>• Not necessarily involves mechanisms to facilitate SBCE’s principles</li> <li>• Not necessarily focuses on knowledge based paradigm</li> </ul>
Platform design	<ul style="list-style-type: none"> <li>• Standard modules can be designed based on SBCE principles</li> <li>• Variety of design options/customized solutions can be designed from a platform</li> </ul>	<ul style="list-style-type: none"> <li>• SBCE is a process to build an optimal platform. Thus, platform is the result and SBCE is the process to design a platform</li> </ul>

<sup>7</sup> The comparison is based on the author’s analysis and opinion.

<sup>8</sup> Knowledge based paradigm is when the principles (exploration, set based communication and convergence) are supported by knowledge and data using experience, knowledge from past projects’, testing of alternative solutions at different working conditions and frontloading knowledge from downstream functions (e.g. manufacturing, assembly, use, service phases).



Approaches that are seemingly similar with SBCE are compared in this chapter. In general, the similarities of the approaches with SBCE lie on the consideration of multiple alternatives early in the beginning (see Table 3.1). However, looking in-depth to the details there are significant difference with the other approaches. SBCE advances other existing approaches in several ways. Table 3.1 summarizes the differences. Taking Pugh's controlled convergence approach as an example; there are several differences with SBCE on how concept convergence is taken place. In Pugh's approach new solutions are allowed to be reconsidered even late in the process which according to SBCE's principles of 'stay once committed' creates disruption across team members because new concepts might cause reworks. The Pugh's approach doesn't necessarily involve neat principles and mechanisms as SBCE. Principle based developed is paramount to guide designers to be effective. Importantly, there is a difference between Pugh's approach and SBCE related to creating a knowledge based environment in design process. Pugh's approach has little guides or suggestions on how to use knowledge to facilitate the convergence process. In SBCE however, the processes of exploration, set based communication and convergence are facilitated by knowledge gained through previous projects, or testing or frontloading from downstream functions. Thus, SBCE is knowledge based paradigm than other approaches proposed in literature.

In the next chapter 4, the enablers of SBCE will be discussed in detail. Enablers of SBCE are those practices, capabilities, competences or techniques that are necessary to conduct the principles. Extensive literature reviews are conducted to build an integrated framework of enablers. The first use of the framework is to contextualize the discussion on research gaps presented in chapter 5 and the research contributions this thesis proposes in chapters 6 and 7. The second use is for industries who want to apply SBCE process in their development process. The integrated framework will suggest what improvements or changes industries have to make to effectively integrate the principles of SBCE in practice. The third use of the integrated framework is to expand the arguments presented in the literature. In general, the current argument on the convenience of adopting SBCE has limited view. The limitation is that, most of the literature argued SBCE as pursuing multiple designs and converging into one preferred solution (e.g. Terwarch, et al. 2002; Bogus 2006). However, SBCE concepts indicate more than this narrowed view. Therefore, when SBCE is argued along with its associated enablers, it brings more perspectives to industries and expands the discussion on the role of SBCE.

## 4 ENABLERS OF SET BASED CONCURRENT ENGINEERING



This chapter is dedicated to construct the SBCE enablers. ‘Enablers’ in this context implies those elements that are necessary to execute SBCE’s principles in practice. These enablers are built considering literature from different bodies of knowledge in product development such as concurrent engineering, knowledge management, customer value researches, tools, methods, technologies, and lean product development. Five enablers are identified and discussed in this chapter. These are: *customer value research*, which is concerned with the capturing and integration of customer information into SBCE; *people competence*, which deals with the role of mentoring, coaching and strong-leadership in facilitating SBCE; *process practices*, which deals with the role of organization structure, involvements and integrations of stakeholders in SBCE; *intra/ inter knowledge transfer*, which elaborate the roles and the mechanisms of knowledge identification, capturing, documentation, transferring and reusing in SBCE; and *tools/ methods/ technologies adoption*, which is concerned with the analyses of tools, methods and technologies that can be integrated to support the execution of the SBCE’s principles. The intent of building the enablers is to identify their significance in facilitating the SBCE in practice. In this chapter, each of the enablers are discussed in detail and summarized in an integrated framework (framework of SBCE’s enablers). Moreover, some of these enablers are used to design the SBCE serious game (discussed chapter 6), and to develop the SBCE IR methodology (discussed in chapter 7).

## 4.1 Introduction

Five enablers are discussed in this chapter. In section 4.1 these enablers are introduced, and from section 4.2 to 4.6 the enablers are discussed in detail. The chapter will conclude in section 4.7 by reviewing the main issues of the chapter and proposing an integrated framework of SBCE. Moreover, a summary of highlights is provided on the gaps that exist in SBCE literature and practice concerning the principles and enablers that are the focus of this thesis.

From literature review conducted in this thesis, it has been found that in order to successfully execute SBCE principles, there are enablers that should exist or should be practiced. Therefore, in this thesis an integrated framework of SBCE process has been proposed as shown in Figure 4.1. The enablers are grouped as:

- Customer value research
- People competences
- Process practice
- Intra/ Inter knowledge transfer
- Tool/ Method/ Technology adoption.

The proposed integrated framework has three main purposes. The first use of the framework is to contextualize the discussion on research gaps presented in chapter 5 and the research contributions this thesis proposes in chapters 6 and 7. The second use is for industries who want to apply SBCE process in their development process. SBCE is not just pursuing alternative designs, but is an integrated seamless framework that should be facilitated by the enablers proposed in this chapter. Moreover, industries should improve their capabilities in different enabler areas before or along with the implementation of SBCE process. The third use of the integrated framework is to expand the arguments presented in literature. In general, the current argument on the convenience of adopting SBCE has limited view. The limitation is that, most of the literature argued SBCE as pursuing alternative designs and converging into one preferred solution (e.g. Terwarch, et al. 2002; Bogus 2006). However, SBCE concepts indicate more than this narrowed view. When SBCE is argued along with its associated enablers, it brings more perspectives to industries and expands the discussion on the role of SBCE. For example, the objective of pursuing and testing multiple designs in parallel is to identify and capture diverse business and technical knowledge (Ward, et al. 2007). Thereby, the cost of pursuing multiple solutions has to be argued along with the value of creating knowledge about customers, design constraints and others. In the following sub-sections (4.2 to 4.6) each of the enablers is discussed.

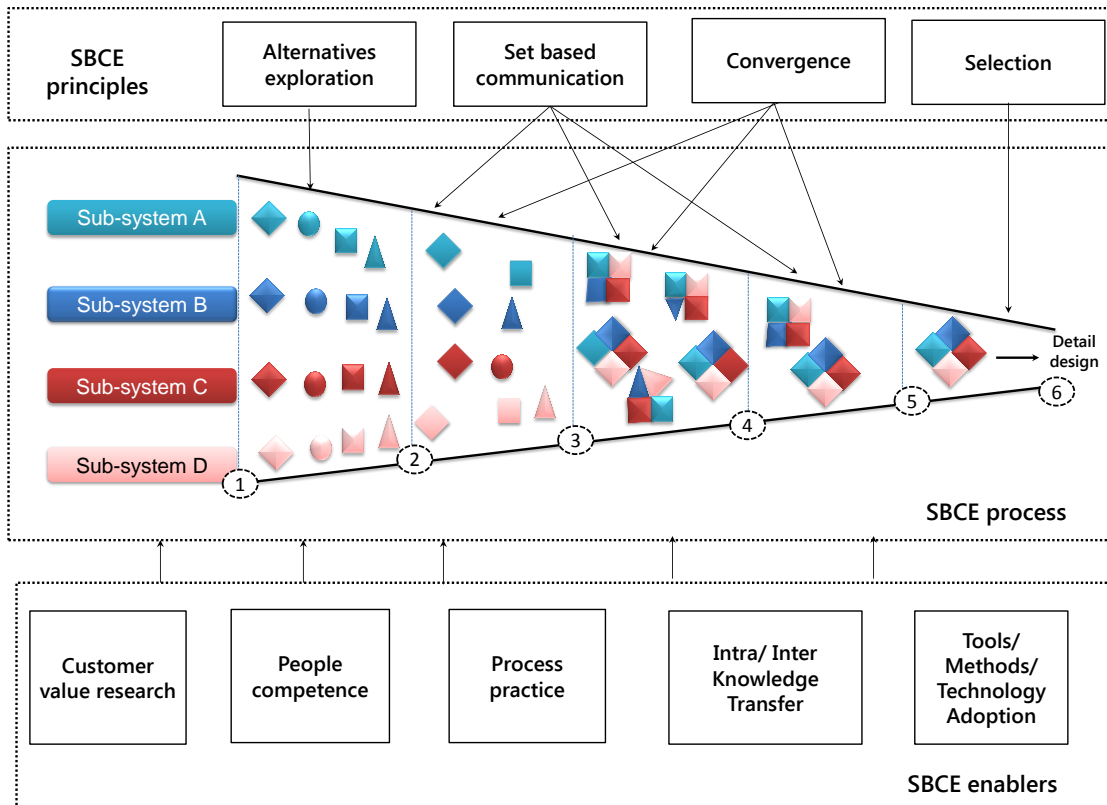


Figure 4.1: Integrated framework of SBCE principles, process and enablers<sup>9</sup>.

## 4.2 Customer value research

Customer value research has been a topic for several years in the past, there has been a wide spectrum of definitions on “what value is” (as listed below) and there are several models explaining the relationship between value and business performances. The purpose of this section is not to extensively review the literature on the topic of customer value research. Instead, the purpose is to show why understanding the right customer value is critical for successful implementation of SBCE.

There are several definitions on what value mean as listed below. The definitions however share similar features. First, value is perceptual and this is probably the most universally accepted aspect of the concept. Indeed, some authors even use the terms “perceived value” or “value judgment” to refer to customer value. That means the consumer’s evaluation of the value of a product or a service is not an objective process but is

<sup>9</sup> The term *SBCE process* is related to the development of a design following the *SBCE principles*. In this thesis, *SBCE process* and *SBCE principles* might be used interchangeably when the principles are mentioned as a whole. Moreover, *SBCE process* and *SBCE principles* are also referred as simply *SBCE*.

influenced by a perceptual distortion of reality, and that might be the main reason why, after all, it is so hard to find a universal definition to this concept.

<i>Some definition of customer value</i>	<i>Source</i>
<i>“The consumer’s overall assessment of the utility of a product based on perceptions of what is received and what is given”</i>	<i>Zeithaml 88</i>
<i>“A customer’s perceived preference for and evaluation of those product attributes, attribute performances, and consequences arising from use that facilitate (or block) achieving the customer’s goals and purposes in use situations”</i>	<i>Woodruff 97</i>
<i>“Customer perceived value in business markets is the trade-off between the multiple benefits and sacrifices of a supplier’s offering, as perceived by key-decision makers in the customer’s organization, and taking into consideration the available the alternative supplier’s alternative offerings in a specific use situation”</i>	<i>Eggert and Ulaga 02</i>

The second common feature that is widely shared between different opinions is that value is situational and temporally determined. Thus, the perceived value of a product can be expected to vary across different types of purchase situations. Moreover, even for the same type of purchase situation, the value of a product can change over time based upon the customer’s past experiences or satisfaction.

Both features indicate the nature of the information about customer value is both imprecise and unstable. Schrader et al. (1993) defined imprecision when the information received is not accurately described. On the other hand, Terwiesch et al. (2002) defined instability of information when it changes overtime. These are the two main reasons (imprecision and instability) why in SBCE the process of studying customer value should be different. The discussion of customer value research for SBCE is divided into two portions: customer value capturing and customer value integration. Each will be briefly discussed as follows:

#### **4.2.1 Customer value capturing**

Traditionally, companies conduct surveys, interviews and industrial value assessments to pinpoint values which can be expressed or stated explicitly (Anderson, et al. 1993). However, the capacity of these methods to capture the intrinsic and unexpressed customer value is weak. Information gathered through marketing survey is poor in capturing the information accurately (Morgan and Liker 2006). Moreover, it is normal that customers might not know what they need today and in the future. In his famous study Wicker (1969) found that there is only a weak correlation between speech and behavior. Wells and Loftus (1984) showed that people’s descriptions of past events are highly fallible. As a result, by using traditional value collection methods alone (e.g. customer survey), it is difficult to get accurate information on what customers really

want today and in the future. As a result, a different approach is necessary before a SBCE process is practiced.

Morgan and Liker (2006) underlined the above facts and explained that SBCE process in Toyota for example starts with effectively capturing customer value information. The chief engineers (CEs) in Toyota spent extensive time at customers’ sites to understand the final users’ experiences. In this way, the engineers will have a more precise idea of the customers’ expectation, and can meter what functions and forms a car should have. The customer requirements are then documented in the form of a concept paper, presented to management, evaluated, refined and eventually translated into a product definition (Ward, et al. 1995; Morgan and Liker 2006).

Logically, the consequence of missing the right customer information is worse in the case of SBCE than in PBCE. Because, in the former case, engineers will explore solutions, teams do extensive communication about sets, and progressively converge into a solution. These processes demand a considerable amount of engineering time. Thus, if the input of customer information is wrong and/or changes, the impacts in PD performances become drastically worse. Therefore, industries have to have effective approaches and methods to capture customer value information before adopting SBCE process.

A summary and comparison of different customer value research methods are presented in Table 4.1. Those methods which enable engineers to get accurate value information are recommended to use in SBCE. For instance: *Field value in use/Gamba* (Imai, et al. 1985; Imai 1997), where engineers assess customers while using a new product and make intensive collaboration with the customer itself or practicing “*Gemba*” (a Japanese word which means “the true source of information”); *Ethnographical studies* (Wells and Loftus 1984; Morgan and Liker 2006), where engineers in this case act as if they are the end users of the product and put themselves in the shoe of the customer.

Table 4.1: Some examples of customer value capturing methods.

<b>Methods of capturing value</b>	<b>Form of documentation</b>	<b>Effectiveness and usage</b>	<b>Advantages</b>	<b>Disadvantages</b>	<b>Source/s</b>
<i>Direct Survey/ Interview</i>	qualitative rankings or rough value propositions	widely used for simple, familiar products, non-technical products	simplicity, fast, most familiar	less effective to capture unspoken needs, low response rate	Anderson, et al. 93
<i>Conjoint analysis</i>	range of numbers for different value attributes	familiar but less used, prevalent for pricing	rigorous and higher accuracy	very expensive comparing to other methods, not	Green, et al. 01

	(e.g. 0-9 range)			effective to capture unspoken need	
<i>Focus group value assessment/Gamba</i>	qualitative assessments	used at design concept stage, familiar in business to business context	effective to capture unspoken needs	need knowledge and experience about technical and market issues	Imai, et al. 85; Imai 97
<i>Contextual Inquires</i>	qualitative assessments	effective to capture technical difficulties in use	effective in discovering customers	customer distraction and behavioral biased	Shillito 01
<i>Customer Defection</i>	qualitative assessments and pareto chart	used in service design	improve services	late feedback, failure to learn from the past	Reichheld 96
<i>Ethnographical Studies</i>	performance targets for new ideas and concept papers	used in Toyota	effective in matching customer and design process	need knowledge and experience about technical and market issues	Wicker 69; Wells and Loftus 84
<i>Open innovation/Co-creation</i>	sharing experience, trends and technologies	used in B2B, supplementary industries	involves multiple stakeholders	stakeholder might not be creative, cultural/change barriers	Chesbrough 03; David, et al. 07
<i>Social Medias and Networks</i>	quantitative and qualitative data	social platform to capture customer information	less costly, effective in capturing value	difficult to manage and update, hard to filtering genuine feedbacks	Nikolaus and Frank 04; Cooke and Buckley 08; Andersson and Rosenqvist 07

#### **4.2.2 Integrating customer value**

Capturing customer value is not sufficient; those values should be effectively integrated into products' features, and delivered to the customer at the right time/ cost and quality. Ward et al. (2007) describe the concept of flow in PD to indicate the role of customer value. Customer value should drive a development process. Engineers should be concerned to achieve the right customer value and avoid wasting their time on non-value adding activities (Browning 2003). One of the non-value adding activities in PD is "over design/over processing". This includes adding functions and features in design concepts which don't have any value to the customer (Bauch 2004; McManus 2005; Kato 2005). In fact, researches show that non-value adding activities (including over design) have considerable negative impacts on PD performances, such as reworks, incurring additional costs, missing opportunities and so on (Oehmen and Rebutisch 2010; Pessoa,

et al. 2008; Rossi, et al. 2011/a). In SBCE process, the issue of integrating customer value and striving to its achievement has to be taken as important. Otherwise, its potential to improve PD performances in industries will be limited. Therefore, mechanisms that facilitate value integration into product and process are considered as part of the integrated in SBCE process, as shown in Figure 4.2.

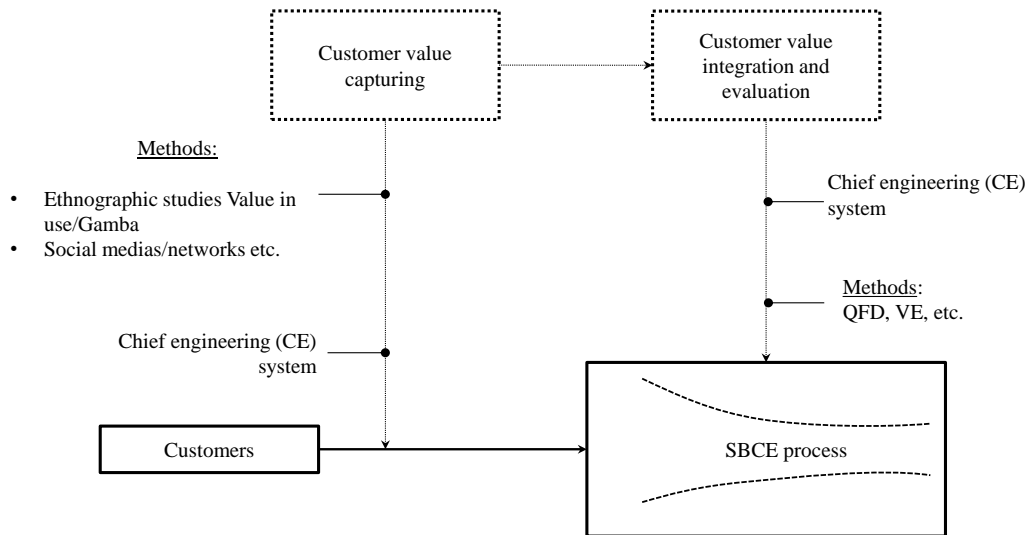


Figure 4.2: Customer value research as enabler for SBCE process.

There are different mechanisms that help companies to effectively integrate customer value into product and process to facilitate SBCE. For example, the chief engineers (CEs) system involves engineers which are well experienced in technical knowledge and customer researches. CEs conduct ethnographical studies at customer sites and understand what customers need. Then, the engineers act as integrator between customer and the developing company (Morgan and Liker 2006). Whenever there are conflicts between sub-system engineers during SBCE, the CEs decide what to do, and always lead development teams to achieve the defined customer value.

There are also tools which can facilitate the integration of customer value into product and process in SBCE. For example, the prevalent QFD (Quality Function Deployment) tool can be used to translate the customer values into product and process quality characteristics (Akao 1990/a/b). QFD perhaps is the most well-known and well-studied tool (Chan and Wu 2002). However, one should notice that, it can be used in both PBCE and SBCE. Liker, et al. (1996) and Cristiano, et al. (2000) did survey studies on the usage of QFD in U.S and Japanese industries and found out that QFD is used in different ways in the two countries. In U.S industries, QFD is a tool to primarily execute point based practice: to fix design specification early, to select a design concept before feasibilities are well studied and to plan development and production activities. On the other hand, Japanese industries use QFD to primarily execute SBCE. The use of QFD for set based practice allows flexibility in Japanese industries (Liker, et al. 1996). Because, at early phase of design, the



customer value (in the form of requirements) are not fully known and are subject to changes. Thus, the matrices and the checklists used in QFD are based on broad definition of customer requirements (range of values). The design and production plans also consider these ranges of possible customer requirements. For example, manufacturing department starts ordering dies with broader specifications (not fixed) and consider alternative manufacturing processes. Thus, if there are any changes in the middle of the PD process, the plan is flexible enough to adjust.

Value engineering (VE) is another systematic technique used to make sure that the customer value identified from customer research is achieved (Cooper, and Slagmulder 1997). In VE, customer value is assumed to be the ratio of function to cost and can therefore be increased by either improving the function or reducing the cost (Cooper, and Slagmulder 1997). So, VE can be used in SBCE process to facilitate set based communication, convergence and selection processes. Cariaga, et al. (2007) developed an integrated model based on VE and QFD approaches for eliciting and evaluating design alternatives. The model has been used to evaluate design concepts based on their value indices for the final customer. QFD used in the model as a mechanism to translate the customer information into some value attributes, while VE used to provide measures to evaluate the performance a design alternative based on the value attributes designed. Such kind of model can be utilized in SBCE process to evaluate alternative concepts based on the right customer value measures. Moreover, it is also possible that some concepts can be merged to maximize their value contents (Cariaga, et al. 2007).

In summary, customer value research is an important enabler of SBCE process. Careful examination of customer value and proper integration into PD is paramount, otherwise a SBCE implementation initiative turn out to be a futile effort. In order to support SBCE, therefore, effective methods, tools and techniques should be used to precisely capture and integrate customer value information in SBCE.

### **4.3 People competence**

The role of the chief engineers (CEs) is critical to ensure customers' orientation throughout the entire duration of a project. In particular, CEs facilitate SBCE process by predicting customer value information with greater accuracy, and make follow ups to make it stable throughout a project. CEs skills and competences will also be used to integrate the customer requirements in SBCE process to explore concepts, facilitate communication and integration. This coordination function is of major importance for the success of SBCE and the success of a design project.

In SBCE, engineers have to do a lot of technical works such as exploring of alternative solutions, evaluate their inherent tradeoffs, and test the alternative solutions to check feasibilities. These activities make

technical specialties indispensable with dedicated expertise in a particular field and knowledge domain (Ward, et al. 2007). I.e. engineers will specialize on particular sub-systems. For example, in automotive design, a designer could specialize in engine or styling design. Such specialization of knowledge and skills support SBCE process in order to effectively explore innovative sub-system solutions, evaluate sets and testing solutions (Ward, et al. 2007). As Womack and Jones (1994) pointed out, specialized functions serve as schools which continuously gather knowledge and best practices and teach it to their members. This ensures that engineers have standard skillsets which enable them to fulfill their particular tasks in the best way possible in SBCE process (Ward, et al. 2007).

However, in traditional organizations engineers often do not spend long enough time in the same functional or specialized division. Career paths are built by substituting technical tasks with general management and administrative tasks (Hoppmann 2009). This practice is a risk for successful implementation of SBCE process. Ward et al. (2007) asserted that knowledge will be wasted when engineers change from being designers to managers in short period of time, without making technical foundations beforehand.

First, when less experienced engineers become managers, their technical abilities to manage a SBCE process will be under question, which creates knowledge gaps (Ward, et al. 2007). In Toyota, for example, it normally takes a minimum of 10 to 12 years before an engineer becomes eligible for promotion to a first-level management position (Morgan and Liker 2006). This indicates that for a SBCE process to be effective, engineers should have a deep understanding of their specialized area before promoted to management levels (Schuh, et al. 2007).

Second, new engineers should get proper mentoring and training activities to foster SBCE process. Training and mentoring are key to transfer knowledge from experienced to novice engineers (Morgan and Liker 2006; Ward, et al. 2007). One factor that contributed to the success of SBCE process in Toyota is the culture of comprehensive use of mentoring as one of its core leadership principles (Morgan and Liker 2007). For example, new engineers in Toyota, after being selected in a rigorous admission process, first have to spend about half a year assembling and selling cars. This procedure is supposed to increase their understanding of value as perceived by the end customer and production.

In sum, SBCE process is effective when engineers and managers are skilled in understanding customer needs and integrating those needs in the design process. Mentoring and training activities for engineers are paramount for effective implementation of SBCE. Moreover, following specialized carrier paths in particular sub-systems knowledge domains is part of enabler for SBCE. Figure 4.3 shows an integrated competence scheme necessary to pursue SBCE process based on skill, experience and knowledge.

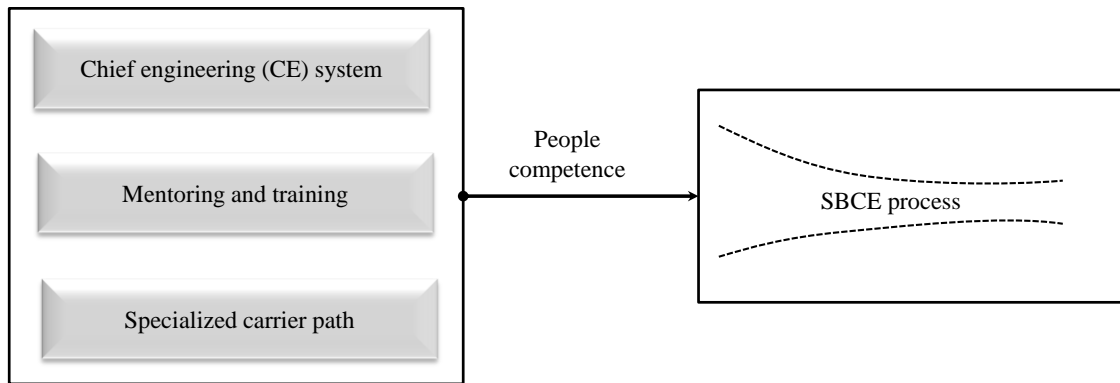


Figure 4.3: People competence as enabler of SBCE process.

## 4.4 Process practices

Process practices in this thesis are concerned with those design and development activities that facilitate the SBCE process. Within process practice category, there are several key enablers that can support the exploration, communication and convergence principles in SBCE. Process practice enablers are grouped into three main perspectives: *organization*, *involvements* and *integration*. *Organization* is concerned with the way a PD process is structured. *Involvements* is dealt with the systematic integration of stakeholders, this further divides into three aspects such as, early involvement of customer, suppliers involvement for SBCE and involvement of internal functions (e.g. testing, manufacturing and so on). *Integration* is concerned with how teams involved in PD process integrate each other and how problems are handled at control points in PD process. In this section, each of these process enablers is discussed in the realm of their implications for SBCE.

### 4.4.1 Organization

As discussed above in section 4.3, specialized carrier path has been mentioned as one enabler for SBCE process. The rationale behind was that, effective innovation in SBCE can be achieved if engineers are well experienced and knowledgeable in their respective specialized sub-system areas (Morgan and Liker 2006; Ward, et al. 2006; Hoppmann 2009). However, organizational structure based on functional or specialized areas might limit communication and integration, which are key aspects in SBCE process (Morgan and Liker 2006; Ward, et al. 2006; Hoppmann 2009). In order to benefit the merits of specialization and achieve integration, a matrix organization is favorable for SBCE (Morgan and Liker 2007; Hoppmann 2009). In matrix organization, engineers are grouped according to their specialized area and the chief engineers integrate the activities of a project across functional groups (Morgan and Liker 2007), see Figure 4.4 below.

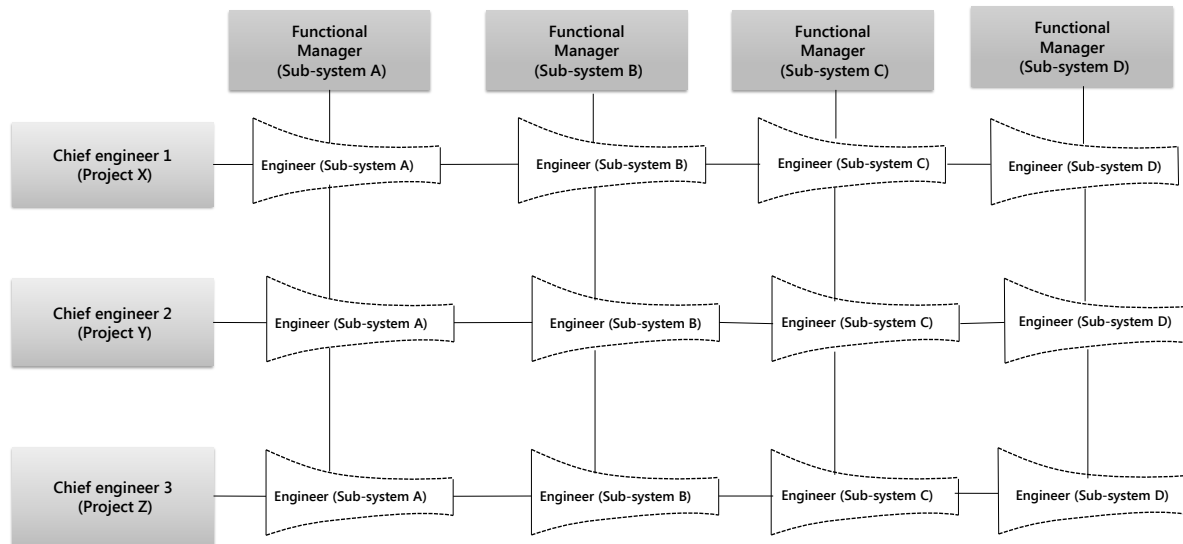


Figure 4.4: Product development matrix organization as enabler for SBCE process.

In Toyota, for example, chief engineers (CEs) check the adherence of a project to schedule, cost and performance targets set at the beginning (Schuh, et al. 2008). They communicate directly and frequently with designers and engineers who work in sub-system levels. In contrast to the role of a classical project manager, however, CEs role is not limited to administrative tasks, personnel decisions and project controlling. Instead, they are strongly involved in the development of the technical details.

While the specialized engineers focus on the development of solutions for subsystems and components, the CEs as the lead engineer is mainly concerned with the integration of these subsystems to an overall high performance, high-quality system (Morgan and Liker 2006). Moreover, it is also the role of the CEs to resonate the “voice of the customer” to ensure that program objectives and the goals among the cross-functional team are well aligned (Haque and James 2004). They “own” the program and, due to their far-reaching leeway, can be held fully responsible for project outcomes (Oppenheim 2004; Karlsson and Ahlstrom 1996; Sobek, et al. 1999; Kennedy 2003; Ward, et al. 2007).

One paradox that exists in Toyota’s PD organization is that, the CEs irrespective of their large responsibilities, their authority to manage engineers are limited. Apart from a small team of staff, sub-system specialized engineers do not report to the CEs. It is up to the functional managers who supervise the engineers, assign them to projects, evaluate their performance and decide on promotions. In this way, CEs are freed from administrative tasks and focus on integrating customer needs across the functions. What give CEs a resound respect across engineers are their renowned experience and knowledge among all the engineering and functional managers (Morgan and Liker 2006; Oppenheim 2004; Kennedy 2003; Ward, et al. 2007).

In summary, SBCE demands a PD structure where specialized skills are used to explore and test solutions in SBCE process. At the same time, CEs will strive to achieve integration and communication across the specialized functions and lead value delivery in SBCE process.

#### **4.4.2 Involvement**

The second category of enablers from a process practice perspective is the involvement of stakeholders in SBCE process. Stakeholders in this sense can be customers, internal functions (e.g. testing), and key suppliers. The detail discussions of involving customers in SBCE process have been discussed section 4.2. In section 4.5, more will be presented about the involvement of internal functions to facilitate knowledge identification and capturing process in SBCE. This section primarily extends the discussion of suppliers' involvement in SBCE process.

Liker, et al. (1996) studied Western and Japanese automotive OEMs (Original Equipment Manufacturers) and their relationship with suppliers for SBCE process. The study exhibit the Western OEMs work with a large number of suppliers for every part. Before approaching the suppliers, they define detailed part specifications, invite for tenders and (mainly based on price as a criterion) award the business to a supplier. This practice resulted in a situation with adversarial relationships between automakers and outside suppliers. OEMs have often used their market power to extort low prices from suppliers. Suppliers, in turn, have been reluctant to share inside information with OEMs, fearing that their customers could use this knowledge against them in the bidding process. After being chosen as the supplier for a particular part, they have to inevitable use changes in the development phase to raise their initially negotiated price (Liker, et al. 96; Morgan and Liker 2006; Ward, et al. 2007). The process of price negotiation with a large number of suppliers usually requires a high amount of resources on the part of the OEM, resulting in large purchasing organizations which are responsible for the correspondence with the suppliers (Liker, et al. 96; Morgan and Liker 2006; Fiore 2004).

Companies practicing SBCE have different approach regarding their relationship with their key suppliers. For example, companies such as Toyota and other Japanese automakers have a much smaller supplier base to work on in long term bases (Liker, et al. 1996). These suppliers are involved from the early beginning of a project, to forward alternative component designs and give ideas about technological opportunities and risks (MacDuffie, et al. 1996; Morgan and Liker 2006).

Toyota for example divides its supplier base into four (Morgan and Liker 2006): *contractual suppliers*, who supply simple commodities such as nuts, bolts, brackets and spark plug which Toyota orders via catalogue; *consultative suppliers*, who produce slightly more technically complex parts like tires and they frequently report their innovations to Toyota; *mature suppliers*, compared to the previous two, suppliers in this category

have stronger engineering skills and design their product according to only general specifications given by Toyota; and *partner suppliers*, which are large and highly capable suppliers which develop, produce, and supply complete sub-systems and these are technically autonomous to make decisions on behalf of Toyota.

Relationship between Toyota and the last two categories of suppliers exhibit a SBCE approach than a traditional PBCE. Usually, they are not given detailed specifications on the part they have to deliver. Instead, they are assigned the responsibility for a particular subsystem and help draw up the specifications for their module by actively participating in the design process (Liker, et al. 1996; Karlsson and Ahlstrom 1996). Toyota gives only general functional and interface requirements including cost and weight targets, but without detail specification across each target. The suppliers are free to choose solutions as long as they meet the general requirements, which frequently checked by the CEs at Toyota (Sobek, et al. 1999; Ward, et al. 2007). This exhibit a set-based philosophy in the relationships, because suppliers will take a rough requirement and able to explore alternative solutions, and delay decision as late as possible until the necessary knowledge is uncovered to make decisions.

In SBCE, suppliers make drafts, simulate and conduct tests of solutions. Toyota expects its suppliers to explore the trade-offs among different requirements, back decisions with test data and demonstrate designs by delivering fully functional prototypes early in the process (Liker, et al. 96). In some cases, suppliers are asked to show 10 up to 50 alternative prototypes and their tradeoffs (Ward, et al. 1995; Sobek, et al. 1999). While in traditional companies, a supplier for a particular component is picked at an early stage, at Toyota suppliers are asked to present alternative solutions, present the feasibilities of the solutions, and will develop sub-systems in parallel with the Toyota's designers.

In summary, involvement of important suppliers play important role in SBCE. Their inputs increase the efficiency and effectiveness of the activities involved in exploring, communicating and converging sets. Moreover, since they are experts in their area, the tradeoff assessment they bring give a sound base to make decisions based on data for OEMs.

### **4.4.3 Integration**

Integration in SBCE is needed to make negotiation within functional teams involved in development. Integration is also need to eliminate subsystem solutions which are incompatible and infeasible, taking different functional perspectives into considerations. Further, integration is essential to facilitate team building and knowledge development about performances of others' subsystems solutions (Ward, et al. 2007; Liker and Morgan 2007; Oostewal 2010).

SBCE demands effective negotiation and convergence of solutions should occur. However, these convergence processes for both designs and requirements mandate a slightly different management approach than is normally used in engineering design (Sobek, et al. 1999). In PBCE, completion of design activities are controlled by phase-gate controls (Cooper and Kleinschmidt 1993; Cooper, et al. 2002; Cooper and Edgett 2008). Traditional phase gate methodology promotes progression of product development linearly through distinct phases (stages) of development (Oostewal 2010). However, the targets set in these gates are the assumption of what the final design looks like (e.g. specifications, cost targets, and so on). The targets however found to be infeasible at the gates because of the inherent nature of the process itself. Often, customers change their requirements, suppliers found to be incompetent to deliver the specifications or design fails to meet expectations. Moreover, these changes result in reworks and cause the project to be delayed exceeding the budget. As a result, SBCE process should avoid creating gates that are built on this wrong assumption about the nature of design and development process. Allen Ward called this assumption and the status quo of phase-gate approaches as “evil” (Oostewal 2010, pp. 148).

In SBCE, gates are substituted with integration events (Ward, et al. 1995). Integration events as opposed to design review or gates are points where multiple functions show the performances of explored alternatives and receive feedback from other sub-system team members or CEs (Oostewal 2010). Usually, sub-system functions bring with them prototypes to facilitate the integration events (Wheelwright and Clark 1992). The sets explored are useful tools for managing the design process itself. The size of a set is an indication of the feasibility of the remaining design alternatives (Sobek 1997). If a set is still very large, it indicates that engineers are still uncertain about the design. When a set becomes small, on the other hand, it demonstrates that engineers are confident that they are nearly at the final solution. Thus, process gates serve as formal points in the development process at which managers and engineers can review how large various sets are. Sets that are larger than others provide managers and engineers with a clear signal as to which aspect of the design are progressing more slowly than others, and developers can identify aspects that require more attentions. Hence, in addition to aiding engineers communicate with one another, sets help engineers and managers control the design process (Bernstein 1998; Oostewal 2010).

To facilitate such integration events in SBCE process, Toyota for example set up special rooms what they call it in Japanese as “Obeya” room which serves as venue for regular meetings between CEs and the leaders of the functional groups (Morgan and Liker 2006). On the walls of the Obeya room, the functional engineers post the latest information on the status of projects. In traditional design review meetings, most of the time are wasted arguing without clear data and knowledge about design performances, and its effectiveness is very poor (Oostewal 2010). However, in Obeya room, teams from different functional areas open dialogue and negotiation process using data and knowledge, thanks to the generated tradeoffs and limit-curves from

different functional perspectives (Ward, et al. 2007). Therefore, integration event that brings functional teams together along with their data will facilitate flow in design process and build a true concurrent engineering.

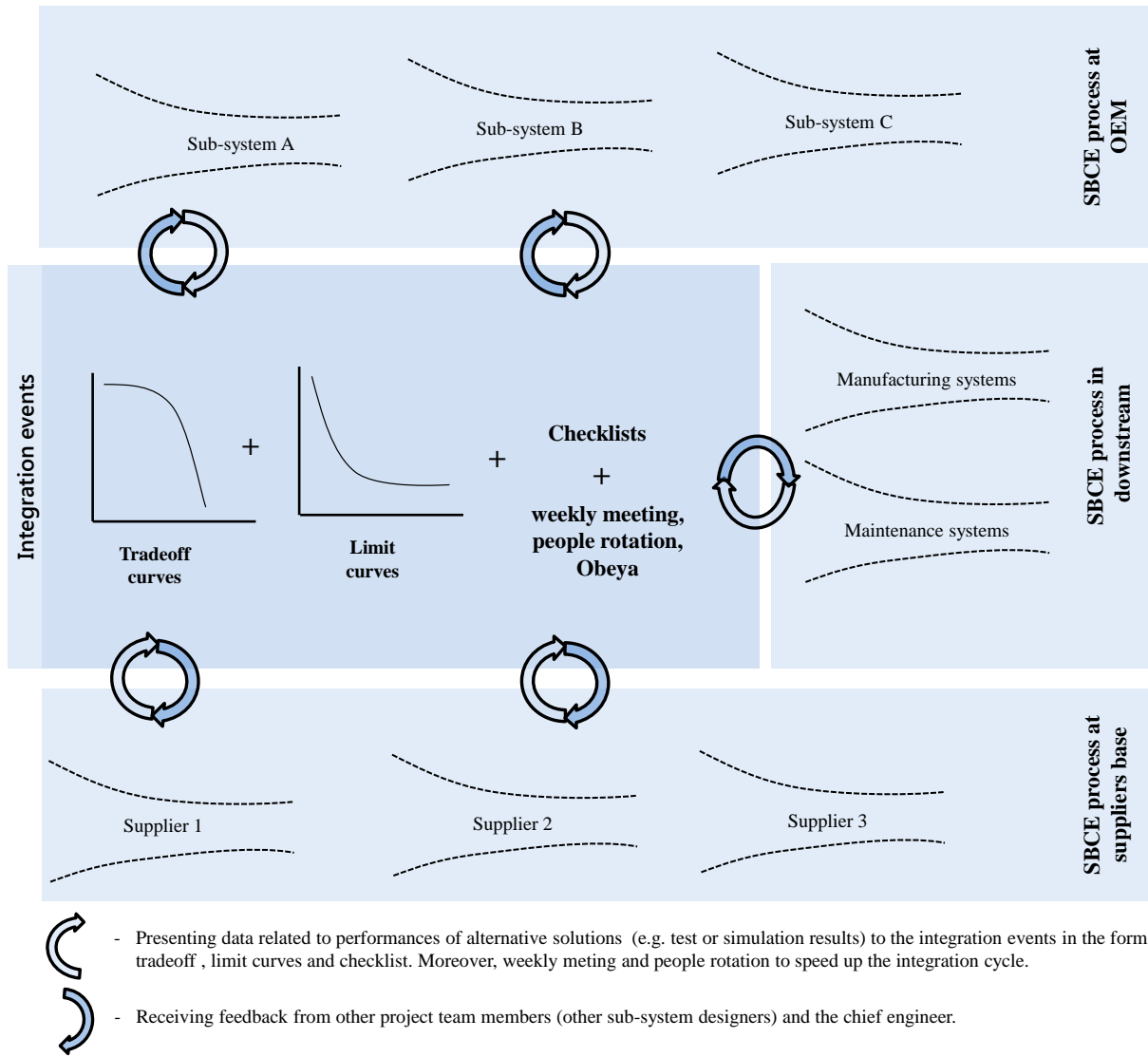


Figure 4.5: Involvements and integration in SBCE process.

In summary, effective process practices such as matrix organization, stakeholders' involvement and integration events will facilitate the exploration, set based communication and convergence principles of SBCE. Otherwise, SBCE will be chaotic and inefficient without such practices in place. Moreover, throughout these practices, knowledge from internal design activities, suppliers, manufacturing and field tests will be integrated to create a robust SBCE process. Figure 4.5 shows a schematic representation as the summary of the discussions on involvement and integration in SBCE.



## **4.5 Intra/ inter knowledge transfer**

Perhaps, one of the key enablers in SBCE process is knowledge capturing and transferring. Allen Ward, the pioneer of SBCE, expressed product design and development as a knowledge creation factory (Ward, et al. 2007). What makes design and development process different compared to production is that, in the former case designers are confronted with new problems and have to create new knowledge to solve those problems in their design activities. One of the critical sources of waste in PD is bad management of knowledge (Bauch 2004; McManus 2004; Kato 2005; Pessoa, et al. 2008). Bad management of knowledge in PD has two sides in it. First is lack of sufficient knowledge creation and documentation within a project (intra knowledge capturing and documentation). The second is the lack of knowledge transfer and use across multiple projects (inter knowledge transfer and use).

### ***4.5.1 Intra knowledge identification, capturing and documentation***

As mentioned in section 2.2.2, the traditional PD is inherently flawed due to the design-test-build doctrine. Team members involved in a PD are normally considering design problems as predictable and look for solutions which are known to them. Kowalick (1998) has expressed this phenomenon as “physiological inertia” when problem solvers are normally look for solutions in their mental solution space, i.e. looking solutions from what they know. However, PD is very unpredictable and unknown sources of failures might occur in different phases of a product’s life cycle. SBCE shift the traditional dogma of the physiological inertia and the design-build-test doctrine to a more knowledge based PD and test-build-design approach (Kennedy and Harmon 2008). In SBCE, engineers will frontload the design process with knowledge from upstream and downstream activities. This can be achieved through testing a solution by intentionally vary parameters early in the development process to explore and understand the limits of what is feasible or testing multiple design alternatives at different sets of working conditions. Then the product is designed with the knowledge of those parameters (Ward, et al. 2007; Oostewal 2010). Such practices are much more effective in understanding and capturing the unknowns in design problems. Furthermore, the knowledge capturing mechanisms of SBCE (tradeoff curves, limit curves and checklists) are effective to document and visually represents data and knowledge for understanding and sharing purposes.

### ***4.5.2 Inter knowledge transfer and use***

Several studies have shown that even highly innovative products strongly depend and build upon knowledge of older products. This knowledge, if not appropriately captured, has to be continuously regenerated (Thomke 2000; Morgan and Liker 2006). For example, Watkin and Clark (1994) found that problems are

often repeatedly solved in consecutive projects. Similarly, in a study of field problems with two novel process machines, von Hippel and Tyre (1994) discovered that of 22 problems identified after installation, 15 involved information that had existed prior to installation. In 10 of the cases the information had simply not been transferred by the designers.

However, test results, simulation results, lesson learned documents are very daunting to revise for engineers in traditional companies (Liker and Morgan 2006; Rossi, et al. 2011/b). Because, the transfer of such knowledge across functions and projects are by transferring engineers and/or using writing long technical documents/ extended reports. For engineers (“knowledge or creative workers”) these are not effective to understand what lesson has been learned in the past or in another project in different place by different teams (Brown 2007; Mascitelli 2007).

The creation of knowledge and effective transferring to subsequent project is paramount in SBCE. At Toyota, for example, for every major part of a vehicle there is a part-specific checklist containing what the company has learned over the years; often visual information regarding good and bad design practices, performance requirements, critical design interfaces, critical to quality characteristics, manufacturing requirements as well as design standards. Each sub-system specialist keep the tradeoff curves and performance checklist to communicate among other engineers, and these instruments also be pulled in subsequent projects to begin from what has been achieved in previous projects (Sobek, et al. 1999; Morgan and Liker 2006; Ward, et al. 2007).

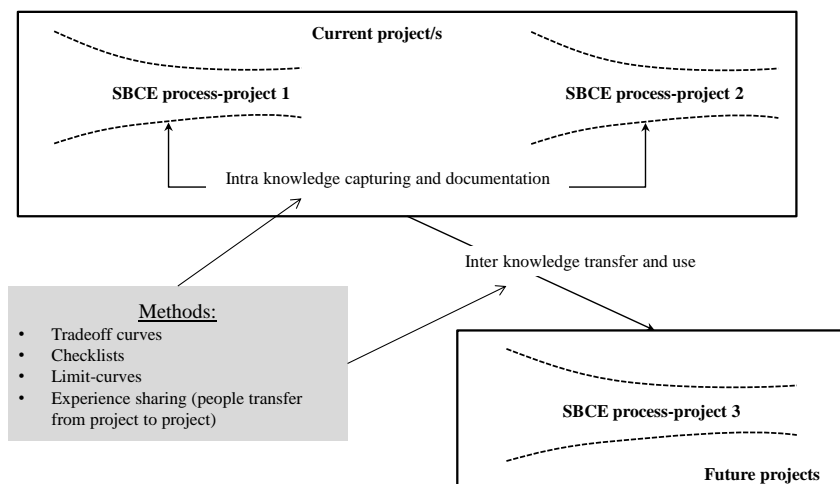


Figure 4.6: Intra/ inter knowledge capturing documentation, transfer and use in SBCE process.

In summary, design is a knowledge creation factory. Effective design knowledge identification, capturing, documenting, visualizing, using and reusing are all paramount for the success of PD performances and for a company’s competitive advantage. SBCE process is a paradigm that foster and transfer traditional PD to a

knowledge based environment, both within a project and across projects. Figure 4.6 shows the summary of the discussions about intra/ inter knowledge transfer as enablers for SBCE process.

## **4.6 Tools/ methods/ technologies adoption**

The last enabler for SBCE is the adoption of systematic tools, methods and advanced ICT (Information and communication) technologies. There are several of such enablers that have direct and indirect relationship with the principles of SBCE. Some of these enablers are already mentioned in the previous sections e.g. QFD (Quality Function Deployment), Value Engineering (VE), tradeoff curves, limit curves, checklists. In fact, some tools are used by Toyota or Japanese manufacturers to support the SBCE process, e.g. QFD (Liker, et al. 1996). But, in general, there are very limited researches that investigate the relationships or the application of already existing tools, methods and technologies with SBCE process. Nevertheless, some of the elements of SBCE process have been addressed by several researchers with or without referring SBCE.

Reviewing all the available tools, methods and technologies that can support SBCE process is out of the scope of this thesis. However, brief overviews of some of these enablers are explored to give a glimpse of how SBCE can be effectively and efficiently implement along with the enablers.

In order to make a concise assessment, the relationship of the enablers with SBCE concept is grouped according to the different phases of the SBCE process. They are: capturing and integrating customer value, exploration of alternative sets, communication of sets of solution within design teams, convergence of sets of solutions and selection of a final design. Note that, some of the tools or methods or technologies can be used to facilitate several phases of SBCE process. For example, VE method can be used to eliminate design solutions which found to be inferior in an early phase of SBCE process, and it can also be used to select a final solution at the end of the process (Cooper and Slagmulder 1997). In another example, tradeoff curves can be used to explore solutions, communicate sets of solutions with teams and it can also be used to select a final product (ward, et al. 2007).

### ***4.6.1 Capturing and integrating customer value***

As mentioned in section 4.2, SBCE process should begin with a good understanding of what the customers are looking for. Even if the process starts with imprecise customer requirements, enablers of SBCE should be in place to guarantee that the design efforts are made in the right directions. Otherwise, all the process will be in efficient and ineffective much worse than PBCE. Therefore, tools/methods/technologies for customer value research in SBCE process should facilitate accurate predictions of customer value effectively which are stated explicitly or unexpressed ones.

Although it has been still a major methodological problem to capture such values, several methods exist (Anderson 1993; Kenneth 1996). List of methods that can be used in SBCE are presented in Table 4.1 above. Some of the methods are briefly explained below.

Shillito (2001) proposed a method called “*Contextual Inquires*”. In this method, customer value can be captured through questioning the customer while using a product (“A day in the life of the customer”). Reichheld (1996/b) did also propose a method called “*Customer Defection*”. In this method, customers are not asked what they need but asked why they refuse to buy a product. In this way, it is more sensible approach to capture what the customer might not express before, and such information can be used to improve product features. Morgan and Liker (2006) describe also a method that Toyota uses to capture customer value called “*Ethnographical Studies*”. In this method, a team of chief engineers spent considerable time at the customer base and feel how users experiences a product while using it. Since the engineers know the technical details of the product, they can match what the customers might need with technical capabilities. These methods bring the engineers one step closer in understanding customers and would be favored than the traditional survey/interview approaches to capture value in SBCE.

The meaning of customer value has also changed to encompass multiple stakeholders related with the product to be designed rather than focusing solely on end users (David, et al. 2007). This is another challenging aspect in capturing customer value in SBCE. Thankfully, there are emerging methods to encompass multiple views inside a value research theme. For example, “*Open innovation*” and “*Co-creation*” approaches are typically new ways of capturing the voice of multiple stakeholders to be integrated (Chesbrough 2003; Prahalad and Ramaswamy 2004; Ramaswamy and Gouillart 2010). Furthermore, the growing concerns on environmental and societal consciousness have created other arena of values that should be accounted in product development (Figge and Hahn 2006). Environmental aspects can be captured using the so called *Eco-design or DFE/S* (Design for the Environment and Sustainability) methodologies valuing products concepts across their life-cycles such as manufacturing, logistics, use, end-of-life phases (Devanathan, et al. 2010; May, et al. 2012).

Ways of capturing customer value have shown distinctive trends as well; from company driven approaches where customers are asked their opinions and desires within predefined value choices to customer driven approaches where innovation and value creation incepts from customer themselves. Such a trend has been possible with the help of Internet and ICT (Information and Communication Technologies). The ever growing usage of Social Medias and Networks provide ample opportunities to capture stated and unstated customer needs in terms of ratings and feedback (Cooke and Buckley 2008). Nikolaus and Frank (2004) showed an interesting case where customers create their own product concepts and propose their own values.

These methods not only make value capturing process more innovative and effective but also less costly and time consuming.

Another class of methods is also needed to integrate the value captured design features and functions. For this, QFD and VE are two prevalent tools that can be used to translate the customer values into product and process quality characteristics (Chan and Wu 2002; Cooper and Slagmulder 1997). Using these methods it is possible to map out the defined value to technical terms and design variables designers have to change to begin SBCE.

#### **4.6.2 Exploration of alternative sets**

There are several methods and tools found in the literature that can facilitate exploration of alternative sets of conceptual designs and creative thinking (Clegg and Birch 2007). According to Kowaltowski et al. (2010), there are around 250 such methods, tools and techniques exist in academic literature. However, there are very few researches which associate the SBCE process and these tools and methods (Bhushan 2007). The main aim of these existing methods and tools are also to explore conceptual solutions. Therefore, many of the existing tools and methods can be used to support the principle of “Mapping the design space” or exploration of solutions in SBCE. Some of these methods are explained below.

*Brainstorming* is probably the best-known method to stimulate exploration of solutions, where experts from various fields put their ideas forward without prior judgment. There are basic rules to brainstorming: focus on quantity, no criticism, and unusual ideas are welcome since they combine and improve ideas (Kowaltowski, et al. 2010). In Osborn’s (1957) definition, brainstorming is a conference technique by which a group of people attempts to find solutions for a specific problem by amassing ideas. But, this method is not well structured and difficult to track back the idea generation process. Moreover, there is no guarantee that some solutions are left unexplored.

A further progress in brainstorming method is also suggested in literature called *Mental Map or Tree Diagram* (Kowaltowski, et al. 2010). This method is based on the potential of idea generation when structured according to initial concepts. This method is usually associated with the visual representation of ideas, to help the “free association” process of brainstorming. Ideas are classified, structured and visually presented. By mapping information, rapid expansion and exploration of an idea occurs. Analogy of images may be part of this method (Rowe 1992; Lawson 1997).

In the effort of making the exploration and creativity process structured in design, there are growing inputs from academia. *Morphological Analysis, MA* (Ritchey 1998, 2006), for instance, is a method developed by Fritz Zwicky (1967, 1969) for exploring all the possible solutions to a multi-dimensional, non-quantified

complex problem in aerospace industry (Ritchey 1998). MA is based on divide-conquer technique. A hierarchical structure of the designed system (a product or a specific problem) is a basis for usage of the method. The following basic partitioning techniques can be used to obtain the required system hierarchical model: (a) partitioning by system component/parts, (b) partitioning by system functions, (c) partitioning by system properties/attributes, and (d) integrated techniques. Then, for each lower level system, designers explore alternative design ideas and concepts. The difficulty of using such method, however, is that there will be a huge number of alternative combinations to manage. These drawbacks of the method limit its adoption in industries (Ritchey 2006). Moreover, unless the product concept is familiar with the designers, it is difficult to detail the physical and functional breakdown of the product. Because SBCE process is more applicable at conceptual design phase before feasibilities are even established and when data are scarce, it might be a challenge to use such a method in SBCE process.

Another possible method that can be used for SBCE process is Axiomatic Design (AD). Its underlying hypothesis is that there are fundamental principles that govern good design practice (Suh 1990, 2001). AD key components are domains, axioms, hierarchies, and zigzagging. Under the AD point of view, the design outputs pertain to four distinct domains: the customer, the functional, the physical and the process domains.

The design process in AD begins in the customer domain with the identification of the customer needs (CNs), i.e., the features that customers are looking for in the 'design object', be it a product, a process, or any other tangible or intangible system. Mapping between the customer and the conceptual domains is used to find out the functional requirements (FRs) of the design object. Once this is done, another mapping makes the translation of the FRs into design parameters (DPs), which are the set of properties that describe the object in the physical domain. At last, mapping from the physical domains to the process domains leads to the process variables (PVs), which outline how to make the design object (Suh 1990, 2001). Mapping between any two contiguous domains is represented by a design equation. Therefore, more than one design may result from the generation of the DPs that satisfy the FRs. Thus, the outcome still depends on the designer's creativity. However, the design axioms (design rules in AD) provide the principles that the mapping techniques must satisfy to produce a good design, and they offer a basis for comparing and selecting designs (Coelho, et al. 2005).

Looking AD with SBCE perspective, there seems to have synergies among them. AD can provide a robust and structured methodology to translate customer requirements into alternative design solutions through exploring alternative way of deploying functions, parameters and physical attributes. SBCE can also provide principles that support AD. What seems to be not clearly evident in AD is that, there are no good design principles that facilitate knowledge capturing, documenting and sharing. Thus, there are good overlaps between SBCE and AD. But, AD is a time consuming process and those equations used to map out from one

domain to another might not be easily available (Coelho, et al. 2005). These would limit the integration of AD with SBCE for exploration of conceptual solutions.

Another method that can have a very good synergy with SBCE process is *TRIZ*. *TRIZ* (a Russian abbreviation for the Theory of Inventive Problems Solving) was originated by the Russian scientist and engineer Genrich Altshuller (Altshuller 1984, 1994, 1999). In 1948, Altshuller started massive studies of patent collections. His objective was to find out if inventive solutions were the result of chaotic and unorganized thinking or there were certain regularities and patterns which governed the process of creating new ideas and inventions.

After investigating approximately 400, 000 to 2 million of patent descriptions, Altshuller found that only 0.3% of all patented solutions were really new, which meant that they used some newly discovered physical principle (such as the first radio receiver or the first film photo camera). The remaining 99.7% of inventions used some already known physical or technological principle but were different in implementations (for instance, both a car and a conveyer belt may use the same principle as air cushion).

In addition, it appeared that a great number of inventions complied with a relatively small number of basic solution patterns. Altshuller concluded that the vast majority of new inventive problems could be solved by using previous experience. If such experience is presented in explicit way, for instance in terms of principles and patterns, problem solvers can produce inventive solutions for very difficult design problems. Further, it is possible to tremendously lead on further studies which let to discoveries based on basic principles of invention (Altshuller 1984, 1994, 1999).

Altshuller and his colleagues argued that, majority of good inventions or new design concepts are generated while solving *contradictions*. Contradiction is a phenomenon where two requirements cannot be achieved without one to be compromised. There are two fundamental contradictions in any design problem that need solutions. The first one is called physical contradiction and the second one is technical contradictions. Physical contradictions occur when an object has contradictory requirements, e.g. a material should be strong and light at the same time, or an object should be long or short at the same time. Technical contradictions, on the other hand, occur when two requirements are in tradeoffs. For example, when a material's weight is lighter, its strength gets worse or increasing area, increases cost (Altshuller 1984, 1994, 1999; Savransky 2000).

The main purpose of TRIZ method, therefore, is to find solutions to eliminate the contradictions that are inherent into a system (product or service). TRIZ literature indeed proposed several inventive principles and approaches to eliminate contradictions. The general approach to eliminate contradiction can be view as follows: first designers should identify either physical or technical contradictions thereby defining their

specific problem. Then, the specific problem should be formulated to a general problem to use TRIZ general recommendations to solve the problem. Once the designer gets a general idea or solution to the general problem, he/she has to find specific solution to the specific problem under investigation as shown in Figure 4.7 (Altshuller 1984, 1994, 1999; Savransky 2000).

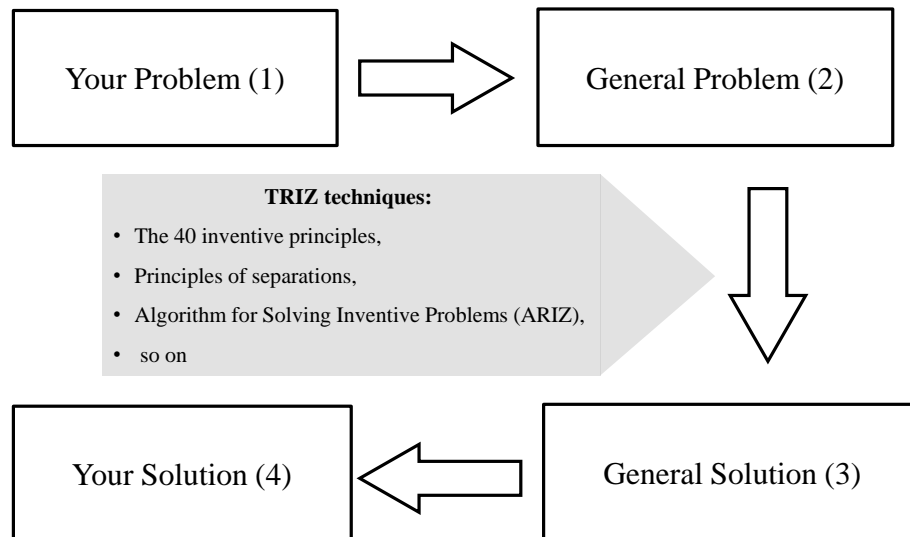


Figure 4.7: Problem solving approaches in TRIZ (Savransky 2000; Hua, et al. 2006).

TRIZ provides techniques to support the idea or concept generation process. The most traditional techniques are the *40 inventive principles* and *principles of separation*. The former is aimed to tackle technical contradictions and the latter for physical contradictions. The TRIZ's 40 inventive principles are based on a standard tabular matrix, where one can take contradictory requirements and obtain different principles that might solve his contradiction. For example, suppose the contradiction is between weight (of a moving object) and strength, and using the table, one can get principles ≠28 (replace a mechanical system with a non-mechanical system), ≠27 (an inexpensive short-life object instead of an expensive durable one), ≠ 18 (use mechanical vibration), and ≠40 (use composite materials). Clearly, these recommendations from the table are very general and one should adopt them to his/her own problem.

Principle of separations, as mentioned before, is primarily aimed to propose solutions for physical contradiction. There are five principles in this technique: separation in time, separation in space, separation in parameter, separation between parts and the whole, and separation up on conditions (Altshuller 1999). For example, aircraft wings should be longer for takeoff, and shorter for landing. This contradiction is a physical one. One can use separation in time and separation in parameter principles to solve the contradiction. As normally seen during flights, the wings of an airplane are longer for takeoff and then pivot back during landing. All the other separation principles are powerful and are applied in many industrial cases, even in service design (Chai, et al. 2005).



The above techniques in TRIZ are traditional once, but TRIZ has evolved enormously in the past decades. There are robust and advance techniques emerging in academia and used in industries. One of the most advanced and evolved technique in TRIZ is ARIZ (Algorithm for Solving Inventive Principle). ARIZ consists of about 85 step-by-step procedures to solve complicated invention problems, and it involves advanced modeling techniques making the process of solution search more structured and robust (Savransky 2000; Hua, et al. 2006).

TRIZ principles and techniques have lots to offer, in particular, to execute the principle of exploration in SBCE. This inkling is also addressed by Bhushan (2007) who suggest a general framework to that integrate SBCE with TRIZ. However, there are much more synergies between SBCE and TRIZ that need future researches. This thesis utilize the synergies between TRIZ and SBCE to develop a methodological approach to identify subsystem areas where SBCE can bring its utmost benefit for customers and companies (see more details in chapter 7).

In sum, *Brainstorming*, *Morphological Analysis (MA)*, *Axiomatic Design (AD)*, *TRIZ* are just some of which methods which are most familiar. There are several other methods which are interesting to investigate. Some of them are listed in Table 4.2. However, the choices between them depend on the contexts of the problem at hand. For example, if a design problem needs simple and less costly approach then methods based on brainstorming can be used. MA and AD approaches can be used if the designs have data to model and represent relations to map function and design parameters spaces. TRIZ is normally used to generate concepts when “out of the box” solutions are needed.

Table 4.2: Example of methods that can support the process of exploring alternative sets of solutions in SBCE<sup>10</sup>.

<b>Methods</b>	<b>Descriptions</b>
<i>Six thinking hats</i>	The hats represent six thinking strategies identified by Edward de Bono, consciously applied in techniques to enhance creativity. Red hat—Emotional thinking. Yellow Hat—Positive thinking. Black Hat—Critical thinking. White Hat—Facts. Green Hat—Creative thinking. Blue Hat—Big Picture
<i>Assumption busting</i>	List of assumptions about the problem is made. Correctness in relation to the problem at hand is tested. New assumptions appear and the most applicable of these are used to find solutions
<i>Synetics</i>	Synetics is a technique to generate and evaluate ideas. In the first session the problem is analyzed. In the second session the problems is described and the scope of action determined. Ideas are generated (using other techniques). Idea springboards are identified to focus on the solution realm. Possible solutions are brought forward. These are analyzed and a new cycle of synetics may have

<sup>10</sup> The descriptions of the methods are summarised from: Clegg and Birch 07; Kowaltowski, et al. 10; Hatchuel and Weil 03.

	to begin if the solutions are rejected until a consensus is reached
<i>SCAMPER</i>	Comes from Substitute, Combine, Adapt, Modify, Produce or find new applications, Eliminate and Rearrange. Questions are made to transform an object or process through the above verbs
<i>Delphi method</i>	The Delphi method is an interactive forecasting method. Relies on input of independent experts, in several rounds, with revised forecast based on output of previous round. Results converge towards “best” solutions using mean or median scores. The number of rounds, achievement of consensus and stability of results are established beforehand
<i>Input–output</i>	Developed by General Electric. The technique identifies new ways of reaching a design goal by focusing on the input (attributes) and final output desired. Requirements and restrictions (specifications) are structured for this purpose
<i>C-K or concept-knowledge</i>	It is both a design theory and a theory of reasoning in design. It defines design reasoning as logic of expansion processes, i.e. a logic that organizes the generation of unknown objects. The theory builds on several traditions of design theory, including systematic design, axiomatic design, creativity theories, general design theories, and artificial intelligence-based design models. Refer, Hatchuel and Weil (2003) for more details
<i>Cause-effect diagram</i>	Related to the concept of searching for causes for problems that might occur due to customer dissatisfaction or technical failures. The method is based on asking chain of WHYs to explore different alternative improvement areas in the product design

### 4.6.3 Communication of alternative sets

Communication is a key aspect in product development, as stressed in several researches (Cusumano and Nobeoka 1998). What is unique about communication in SBCE process is the consideration of sets (Sobek, et al. 1999). Exploring alternative solutions might take considerable time in design, in particular if the design problem is novel (Ford and Sobek 2005). Thus, while a team explores subsystem solutions, effectively communicating them to other teams is paramount. The effectiveness of communication in SBCE process depends on the quality of data presented, the simplicity of the communication, time spent in communicating about the sets. Quality of data as described before is explained in terms of the information contents design teams present. Ward et al. (2007) claim that meetings and design reviews in many companies are not based on data. In SBCE, tradeoffs curves, performance checklists and limit curves provide proven data to make communication and negotiation process effective. Related to data quality issue, the way data are presented should be simple. Design documents which are pages and pages of reports are not effective in SBCE (Kennedy 2003). Rather, simple visual representation of design data in the form of tradeoff curves, checklist and limit curves effectively facilitate communications about sets of design alternatives. Moreover, communication in SBCE should consider the time spent in communication, communicating large sets of alternatives might take time, therefore methods, tools and technologies should be adopted to fasten the communication and negotiation processes.

There are several means in which communication in SBCE process can be efficient and effective. QFD is the prevalent tool that is used to integrate design decisions from customer value capturing to production planning

and control (Akao 1990/a/b; Chan and Wu 2002; Akao and Mazur 2003). Liker et al. (1996) in their survey discovered that most of Japanese automotive industries including Toyota use QFD in SBCE for communication. In addition, there is a strong correlation between the use of QFD in design and existence of set based communication (Liker, et al. 1996). In a sense, it implies that the principles and practices in SBCE process are the evolution of QFD usage. The use of QFD neither implies that SBCE is practiced nor does it indicate QFD substitute SBCE. The real contribution of using QFD in SBCE process is to improve the quality and the simplicity of communication about sets. In fact, most of QFD applications reported in literature are based on point based communication, in particular in the Western manufacturing industries (Liker, et.ia. 1996). That is, QFD is used to translate customer requirements into one design and process alternative. It also indicates that, QFD has been used to freeze requirements early in a design process, which negates the SBCE philosophy of delaying decision (Ward, et al. 1995). In other cases, QFD is also used without a conscious purpose for identifying and capturing customer, design and process knowledge (Chan and Wu 2002). Therefore, SBCE principles and practices should be embedded while using QFD.

Some progress has been made to integrate QFD in SBCE. Kerga et al. (2012) proposed an integrated model to facilitate communication between manufacturing planning and SBCE process. The model proposed is based on QFD and P-FMEA (Process Failure Mode and Effect Analysis). In this model, product designers once explored design solutions, key quality characteristics can be identified (which are important for the customer) and put in the QFD matrix. Then, manufacturing process planners use P-FMEA to identify key process failures that might occur in manufacturing for each alternative design solutions. Each process failures for a given quality characteristics are assigned RNP value (Risk Priority Number). Finally, performance of each design solutions in terms of an aggregate quality index (based on RNP value) and cost of manufacturing can be presented for dialogue between designers and manufacturing personnel. In this way, designers and manufacturing planners effectively communicate about the performances of alternative designs and manufacturing processes.

There is also a stream of researches based on Fuzzy Logic System, FLS to methodologically support communication in SBCE (Wang and Terpenney 2003). Principles such as delaying decision and communication of rough requirements make FLS a prime method to be used. Software based FLS systems are utilized to facilitate the set-based communications, negotiations, and gradual set-reduction process. The software systems are primarily applied in US NAVY and ship design (Singer, et al. 2009; Gray 2011; McKenney, et al. 2011).

In regards to improve quality of communication in SBCE process, there are other established methods that can be used, though are not yet discussed in academic literature. For instance, a method such as “Design for X” (DFX) is worth mentioning. Where, *X* refers to manufacturing, assembly, environment, serviceability,

maintainability, quality and so on. Originally started with a serious of study on design for assembly (DFA) coined by Boothroyd et al. (1994), it considers the assembly constraints (i.e. assembly methods and costs) in the design stages. By using DFA, the estimated assembly time can be used as guideline to find out the design changes that can lead to the reduction of the final cost (Waterbury 1985). Expanding from DFA, Stoll (1988 a/b) developed design for manufacturing (DFM) to simultaneously consider all the design goals and constraints for the product that will be manufactured. Several academic papers about DFA, DFM, or DFMA (DFM and assembly) can be found in literature (Kobe 1990; Kuo, et al. 2001).

These DFX methodologies can be used in SBCE process to improve the quality of communication. Using the DFX methods designers can anticipate concerns from different parts of the product lifecycle and explore tradeoffs between sets of design concepts. Some emerging researches can be mentioned in this regard. For example, Kao (2006) combined design for logistics method with SBCE process. Alternative design concepts are evaluated early in development phases taking logistic performances (transportation time and cost). Similarly, with the emerging trends and concerns about the environmental impacts of a product in its lifecycle some researches are integrating SBCE and DFE (Design for the Environment). For example, Malak et al. (2009) and Kerga et al. (2010) proposed integrated methodologies to consider the environmental performances of alternative design sets from the early phase of design and development process. Therefore, in SBCE process communication quality can be improved by utilizing the already existing methods of DFX, and conscious decision can be taken by different teams involved in a design process.

Finally, it is also worth mentioning the advancements in technologies that can also improve communication in SBCE process. The traditional way of communication in SBCE process lies in building physical models and prototypes. In early phases of SBE process, using low-cost techniques such as mock-ups can first be modeled out of foam, cardboard or wood to gain fast insights on geometric properties (Ward, et al. 2007). Physical prototypes facilitate effective communication by making it simple to discuss and visually depicting the details (Morgan and liker 2006). But, physical prototyping has limitations in terms of depicting complicated features and the time to build them. However, in the last years there are technological advancements to overcome these limitations. Traditional ways of prototyping, therefore, have been more and more complemented by advanced digital technologies such as computer-aided modeling, simulation, digital assembly and 3D prototype printers. The use of these techniques can, if employed appropriately, strongly contribute to identifying and solving problems at a faster rate in SBCE. Iterations can be run earlier and often at a lower cost than it is possible with elaborate, expensive physical prototypes which require time to build (Morgan and Liker2006; Thomke 1998/2000; Thomke, et al. 1998). At the same time, virtual tools such as digital assembly can help to identify many problems before the program enters prototype phase, which can result in a lower number of prototypes needed. The advancements improve in many ways the quality of data

presented, simplify the communication, negotiation process, and reduce the time spent while teams are communication about sets of design solutions in SBCE process.

In summary, there are a lot of opportunities to increase the effectiveness and the efficiency of SBCE process by integrating already existing methods/tools and technologies. Depending on the problem at hand, each of the above mentioned tools/ methods/ technologies can have important significances for communication in SBCE process.

#### **4.6.4 Convergence of alternative sets**

Till now, the discussions on tools/ methods/ technologies as enablers of SBCE process were focusing on exploration and communication aspects of SBCE. The next step is to converge into a design solution that maximizes a customer value (Sobek, et al. 1999). Convergence activities in SBCE process are done before selection. What is unique in SBCE is not how a design solution is selected, rather how and why a solution is eliminated. Elimination of a solution is of course a process of convergence. But, in SBCE process elimination of inferior solutions are done throughout the process as more knowledge is gained through communication, testing and negotiation. Therefore, one thing that must be clear is that, convergence and selection are two different concepts in SBCE. Convergence process is more of knowledge creation process. But, selection is an instant when designers have to choose among available and feasible alternatives.

The tools/methods/technologies described before can be used to enable convergence in SBCE. Checklist, tradeoff curves, limit curves are the prime mechanisms to use for convergence (Ward, et al. 1995; Sobek, et al. 1999, Morgan and Liker 2006; Ward, et al. 2007). Other tools and methods can also be used to facilitate the convergence process such as QFD, FMEA and DFX as discussed before.

On the other hand, selection of a design concept is matured science in PD literature. In fact, selection problem in design is considered to be a decision making and optimization body of knowledge, which have been under academic discussion for the last 300 years (Hazelrigg 2003; Frye, et al. 2010). Nevertheless, it is worth to mention some of the prevalent tools and methods that can be used for concept selection in SBCE process.

- *Pugh selection*: this method compares design alternatives in a matrix format against a number of criteria relating to the performance of the alternatives. One of the alternatives to be compared is selected as a reference design (Pugh 1996). An alternative with the most '+' counts for different performances will be selected as the best.
- *Scoring/ Weighting methods*: this method is based on Borda count (Borda 1781), further discussed in other researches (Saari 1994, 1995, 1999). Teams involved in designing and managing product

development vote the performance of alternative conceptual designs. An alternative with the highest votes will be considered dominating and taken as the best candidate.

- *Analytical Hierarchy Process (AHP)*: this method perhaps is one of the most widely used and discussed in literature. First proposed by Saaty in the 70's, the main breakthrough in AHP method compared to others is the hierarch (Saaty 1980, 2001, 2008). In AHP, a problem is broken down into its smaller constitute parts. At the top of a hierarchy there is the goal or objectives a selection process has to achieve (e.g. improving quality, reducing cost and so on). At the lower levels of the hierarchy more details of the top level objectives are expressed in terms of criterion. Priorities among criteria belonging to a specific level of the hierarchy are obtained using pairwise comparisons. Finally, alternative designs can be evaluated considering its performance on each highest level criterion and the global importance of the criterion itself.
- *Value Engineering (VE)*: in this method, design solutions are evaluated based on the value and cost tradeoffs. Value of a single design solution is defined as the product of three variables: N (the importance of a need a product should satisfy), A (the ability of a product to satisfy a specific need) and f (t) (the availability of a product to target customers). Cost (C) in VE is defined as the total ownership costs a customer should incur across a product's lifecycle (Cooper and Slagmulder 1997; Slack 1999). A design alternative that maximizes the value over the cost will be chosen.
- *Weighted sum of product attributes*: this method seeks to create a utility function for a design such that the best design is the one that maximizes the utility function. The important attributes of a product are identified and assumed utility independent. The product utility function is then constructed as the weighted sum of the attribute measures. An alternative that maximizes the utility function will be chosen as the best one (Howard 1997).
- *Physical programming*: this method is similar to the weighted sum of product attributes. The principal difference is that utilities of the attributes are used in place of the attributes themselves, and the resulting product utility becomes a weighted sum of the attribute utilities (Messac 1996).
- *Taguchi Loss Function (TLF)*: the loss function comprises a preference function, which is intended to represent "a financial measure of user dissatisfaction with a product's performance as it deviates from a target value." Taguchi suggests the use of a quadratic loss function to represent this dissatisfaction. The loss function captures both the expected performance and variation about the expected performance. The best design is the one that minimizes the loss function (Taguchi 1986; Bryne and Taguchi 1986; Taguchi, et al. 2000).

There are several other types of methods used in selection of the “best” alternative once designs are explored and feasibilities are proven in SBCE process. For example, methods based on fuzzy logics (Augustine, et al. 2010; Avigad and Moshaiov 2009) and methods based on multi attribute utility theories (Malak, et al. 2009).

In general, the selection of alternative designs is not the key challenge in SBCE literature nor was its uniqueness over PBCE. Some researchers associate SBCE with a mere selection of an optimal design option using sophisticated mathematical or optimization models (Augustine, et al. 2010; Avigad and Moshaiov 2009; Malak, et al. 2009). However, SBCE is far more comprehensive, in which selection of the best out of alternative designs is one.

## 4.7 Conclusions

The main purpose of this chapter was to build an integrated SBCE framework of enablers needed to execute the principles. The integrated framework for SBCE is summarized as shown in Figure 4.8. The discussions in this chapter are based on extensive literature review and SBCE’s enablers are constructed in an integrated framework.

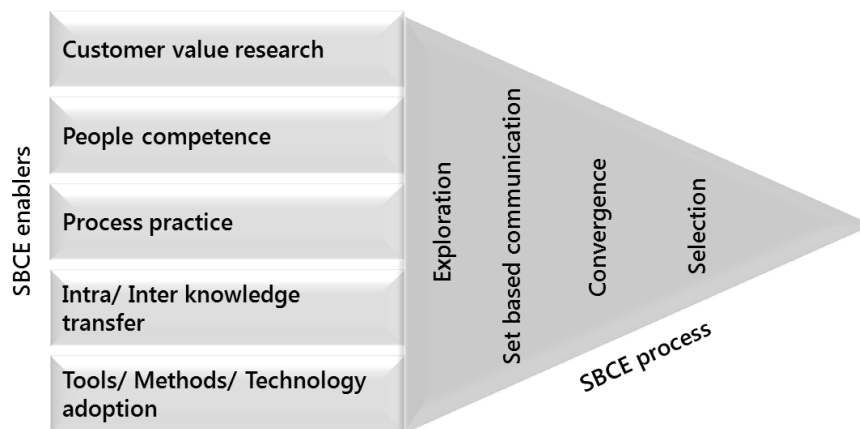


Figure 4.8: Integrated framework of SBCE and its enablers.

From the framework industries should understand that SBCE is an integrated PD model that can be used to effectively develop products and usable knowledge. Moreover, the most important industrial value or advantages are gained from implementing or practicing the SBCE’s enablers as needed to facilitate the principles. That is why, SBCE is referred to as a “process” in this thesis, which encompasses the principles but also the enablers. This view of SBCE is also supported by other researches (Khan, et al. 2010; Hoppmann 2009). Therefore, researches in SBCE have to expand the current narrowed interpretation. Industries also need to build and adopt the enablers if implementation of SBCE is sought. However, there has been a lack of

such framework from literature. The integrated framework developed in this thesis is aimed at creating this comprehensive view of SBCE.

In chapter 5, the two research gaps identified, the thesis's objectives that are addressed in this thesis are explained in detail. Further, the two methodological contributions of this thesis to address the gaps are discussed in chapters 6 and 7.



## 5 RESEARCH GAPS, OBJECTIVES OF THE THESIS AND RESEARCH METHODOLOGIES FOLLOWED



In this chapter the two research gaps are presented. The researcher gaps are named as ‘research gap-one’ and ‘research gap-two’ because of the corresponding parts of this thesis in which they are addressed. Research gap-one is addressed in PART I of this thesis (chapter 6). On the other hand, research gap-two is addressed in PART II of this thesis (chapter 7). The rationale of the gaps and the importance of addressing them are parts of the discussions considered in this chapter. Moreover, the objectives of this thesis and the methodologies followed to address the gaps and meet the objectives are also presented in this chapter.

## 5.1 Introduction

This thesis has two parts addressing two research gaps. The gaps that are discovered and will be the subjects of this thesis are:

- 1) *SBCE awareness level in industries is low.*
- 2) *There is a lack of a methodological approach to identify and prioritize areas where SBCE can be implemented at a product level.*

The two gaps have different targets. The first gap is related to product designers and project managers, and their awareness level concerning the SBCE's principles and enablers. This gap emerged from what has been observed from a field study conducted across industries in Italy. Moreover, there are different reports from other researches indicating a lower level of awareness related to SBCE in industries. Thus, in this thesis, this gap is taken as an important issue to be addressed. If there is a way to increase the level of awareness across industries, it brings contributions primarily to the industry, and also to SBCE's body of knowledge. Section 5.2 is dedicated to elaborate this gap and rationalize the need for a learning method that can improve the awareness level of SBCE in industrial practice. In chapter 6 (PART I), the contribution of this thesis to overcome this gap will be discussed through presenting the SBCE serious game (SBCE SG) designed to bring a hand on experience to practitioners. Moreover, in chapter 6 the validation of the game in Carel Industry is presented.

The second gap is primarily focuses on the SBCE's implementation at a product level. Though the principles of SBCE are sound and its claimed benefits are promising, there are fundamental impediments to practically implement it and obtain success. Because of its extensive nature to apply it to a complete product system, there is a need for a systematically methodology to identify and prioritize improvement areas<sup>11</sup> (e.g. subsystems, components, design factors) where SBCE bring its utmost benefits. Section 5.3 is dedicated for the discussion on the main challenges and research gaps addressed in this part. In chapter 7 (PART II), the methodological contribution of this paper is presented. The thesis proposes a methodology called SBCE Innovation Roadmap (SBCE IR) which can be used to identify and prioritize areas for SBCE implementation. Furthermore, in chapter 7, the validation of the SBCE IR methodology conducted on Adiabatic Humidification System (AHS) is discussed.

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<sup>11</sup> 'Areas' in this thesis is used as a term to generally refer to sub-systems or components or design factors (i.e. design decisions or variables that designers have opportunities and influences to change or improve using SBCE process).

## 5.2 Research gap one – Low awareness level of SBCE in industries

The first part of the research is concerned primarily with a practical gap. Practical in this thesis implies the awareness gap that exists across industries about the principles and enablers of SBCE. The level of awareness in this context can be interpreted into four aspects: *i) the principles and enablers of SBCE are new to companies, ii) the diffusion and practice of SBCE principles and enablers are low in industries and iii) the advantage/ hurdles of implementing SBCE principles and enablers are not well understood by industries.* The rationale of taking the SBCE's awareness as an important research gap that should be addressed is explained below, taking both previous researches and preliminary results of a field study conducted.

### 5.2.1 Awareness gap and the growing interests in industries

From its introduction in 90's (Ward et al., 1995), SBCE is becoming popular in lean PD literature, and there are growing interests in industries to experiment and adopt it. Two examples show the emerging interests across industries. The first example is the US NAVY initiative. The NAVY is launching SBCE initiatives in its project portfolios. Series of researches are emerging from the initiatives (Singer, et al. 2009; Frye 2010; McKenney, et al. 2011; Mebane, et al. 2011). The second example is the European Union (EU) funded initiative called LeanPPD (Lean Product and Process Development, [www.leanppd.org](http://www.leanppd.org)). This EU funded project considers SBCE process at the core of lean thinking in PD (Khan, et al. 2010; Al-Ashaab, et al. 2010). The project involves partners from academia and industries: Automotive, Volkswagen Group (VW, Germany); Aerospace, Rolls-Royce (R-R, UK); Electronics, Visteon (UK), Indesit Company (Italy); and Mechanical (Sitech Sp., Poland). These two initiatives show how interesting SBCE becomes in academia and industries. In both the initiatives, SBCE is strongly believed to change and improve the way the US and EU manufacturing companies design products and manage development processes.

Nevertheless, studies show that the awareness level in industries is still at the fledging state. For example, Bernstein (1998) conducted multiple case studies in aerospace industries in the US. He observed that some principles and enablers of SBCE are applied in some of the industries, and some performance benefits are exhibited. In this study, a company able to reduce 50% rework costs by anticipating design problems from the early phase of design and reusing the knowledge to subsequent projects. However, Bernstein (1998) also reported that, in many of the aerospace industries, the application of SBCE is very limited and there is a low awareness level across the industries.

Similarly, a recent study conducted in Swedish industries showed similar results, SBCE are not well understood and implemented (Raudberge 2010). Some of the industries studied obtained performance

improvements during SBCE implementation in terms of 75% product cost reduction, 50% reduction in lead time, 50-75% improvement in product technical performances, and 50-100 % reduction in project risks, warranty costs and number of engineering changes (Raudberget 2010). In the contrary, others are observed to have negative results applying SBCE. For example, in some industries there were a 25% increment in lead time and a 25% increment in development cost. Some firms obtained neither gains nor losses in adopting SBCE. Those companies who obtain negative results and those who had zero loss/gain were asked about the rationale of the results. Most companies answered “**SBCE is not the way they normally used to work**” (Raudberge 2010).

Related to the awareness gap, there is a wide resistance across industries to adopt SBCE due to its origin. Principles of SBCE and its success stories are based on evidences from large automotive and aerospace industries. The prominent and successful implementation of SBCE in automotive is reported from Toyota’s PD (Sobek, et al. 1999). However, Toyota’s PD has peculiar characteristics that enabled the effective implementation of SBCE process. For instance, Toyota’s success partly can be attributed to its bargaining power to leverage suppliers’ capabilities to facilitate SBCE process. Before bidding, suppliers of Toyota are required to explore several alternative prototypes, test them in different working conditions and bring performance results in the form of trade-off curves (Ward, et al. 1995; Sobek, et al. 1999; Ward, et al. 2007). Toyota thus offsets the extensive portions of SBCE process to partners, and pulls knowledge to support its internal processes. Nonetheless, such kind of opportunities might not be available for many industries (such as in small and medium sized companies). In this regard, a successful implementation and desirable performance outcomes from SBCE cannot be guaranteed for all kind of industries for granted.

From the above research studies, one can understand that SBCE shows benefits when engineers/ managers are equipped with the understanding of its principles and enablers. Otherwise, the effort made to implement the principles and enablers of SBCE become disappointing. Thus, there is a need for a leaning method in which practitioners can use it to experiment SBCE before start implementing it in actual development. This learning method should help industries to increase their awareness level and investigate the applicability of SBCE in particular industrial contexts before adopting it in real design process.

### ***5.2.2 Field study on awareness gap***

In order to find a more detail observations on the awareness gaps across industries a preliminary field study is conducted across industries operating in Italy. Reporting the details of the field study is not the main aim of this thesis. The full report of the study can be found in Rossi et al. (2011/b). Here, the main results that indicate the low awareness level of SBCE principles and enablers (in the surveyed companies) are highlighted to support the rationale of fulfilling the gap.

In total, the industries surveyed were 19. Most of the industries surveyed were operating in Italy, but have markets in global scales. The summary of the companies interviewed are presented in Table 5.1. The empirical research was done with direct face-to-face interviews conducted at site of each manufacturing company with product managers or project leaders. The companies are from different sectors as electronics, microelectronics, mechanical and thermo-mechanical. The duration of an interview was about two hours per meeting, which took place inside each firm. The face-to-face interview was conducted to make sure that the interviewees were clear about the questions posed during the interview, so there were higher levels of interactions to make the questions clearer and avoid misunderstanding.

A semi-structured questioner developed by Cranfield University (Technical Co-ordinator of the LeanPPD project) is used for the in interview. The exhibit of the questionnaire is shown in Appendix (A1). The questions in the questionnaire are composed of 39 multiple-choice questions, grouped into five parts: i) *product development process*, to understand how the PD process is performed within a company; ii) *product design*; iii) *knowledge management*, to understand how design knowledge are identified, captured, documented and reused in subsequent projects; iv) *cost and performance estimation*; and v) *some additional questions*. The results from the field study are briefly summarized in the following subsections.

Table 5.1: Summary of industries surveyed<sup>12</sup>.

<b>Industries</b>	<b>Business</b>	<b>Business size</b>	<b>Type</b>	<b>Customer adoption</b>	<b>Manufacturing volume</b>
1	Heating, Air-condition, Ventilation and Refrigeration (HAVC/R)	Small and Medium	First tier supplier	Tailor made and modular design	Medium
2	Power and Automation Technologies	Large	Orig. Equip. manuf. (OEM)	Standard and modular	High
3	Throttle Bodies and Electronic Control Units	Small	First tier supplier	Standard and modular	Medium
4	Electro-mechanical Systems	Small and Medium	First tier supplier	Tailor made and modular design	Medium
5	Domestic Appliances	Medium	OEM	Standard	High
6	Electronics Control for	Medium	First tier	Standard	High

<sup>12</sup> The table shows 14 industries, the rest 4 are business-units inside some of the industries interviewed.

	Domestic Appliance		supplier		
7	Industrial Machineries	Large	OEM	Tailor made	Low
8	Audio and Antennas Systems	Medium	First tier supplier	Tailor made and modular design	High
9	Safety Radio Remote Control	Medium	First tier supplier	Tailor made and modular design	Medium
10	Heat Transfer, Separation and fluid Handling	Medium	First tier supplier	Tailor made and modular design	Medium
11	Elevator, Escalator and Automatic Building Facilities	Large	OEM	Tailor made and modular design	High
12	High-technology Systems and Telecommunications	Large	First tier supplier	Standard and Modular	High
13	Power Tools and Accessories	Large	OEM	Standard, Modular, Tailor made	High
14	Health and Well-being (Pharmaceuticals)	Medium	-	-	Medium

### 5.2.2.1 *SBCE adoption and effectiveness*

Looking at Figure 5.1, 21% (4 out of 19) of the interviewees reported to follow the traditional method of point based serial engineering (sequential engineering), and express it as the least effective. Concurrent engineering (CE) is the most popular method for product development (reported by 89% of the interviewees: 67% always and 22% sometimes) and shows a high level of effectiveness. SBCE has not yet been fully implemented and accepted as a routine method. However, there have been minor inducements at component levels and the cases of implementation showed good level of effectiveness.

The result clearly indicates a lower adoption level of SBCE in industries. Moreover, its effectiveness is ranked lower than what is expected. As discussed in chapter 2, CE doesn't break the inherent problems in PD, in particular, if the CE is based pursuing a single alternative design. Figure 5.2 exactly shows this phenomena where 86% of the interview companies develop one solution. Even those who consider alternative designs at the beginning (48%) define their choices quickly. The design alternatives which are

eliminated might be potential solutions, but once eliminated without further trade space study, the teams will not have the chance to learn about the designs' performances. More than 81% of the respondents also said that, design specifications change and a concept selected is subject to frequent updates in the process. Therefore, the practices in the industries are predominantly PBCE.

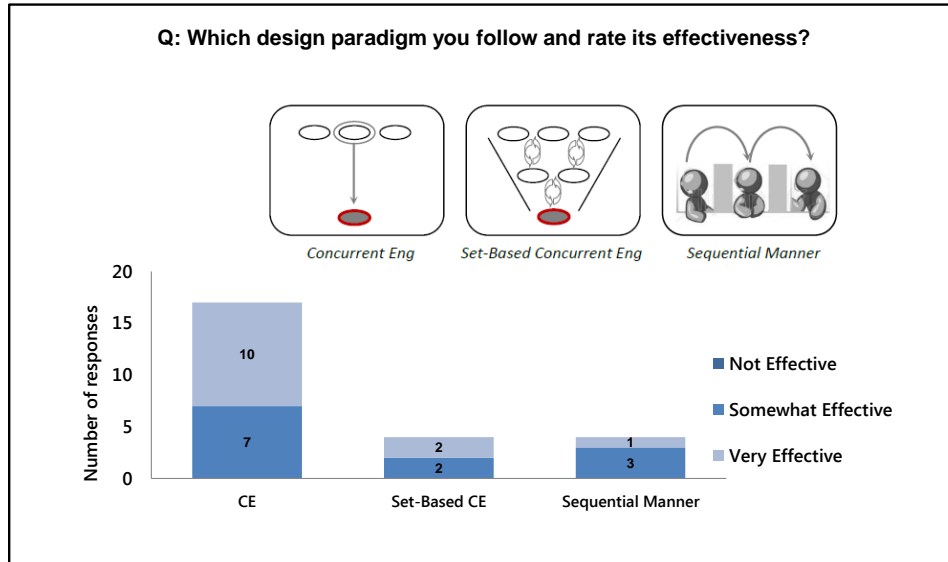


Figure 5.1: Design paradigms followed.

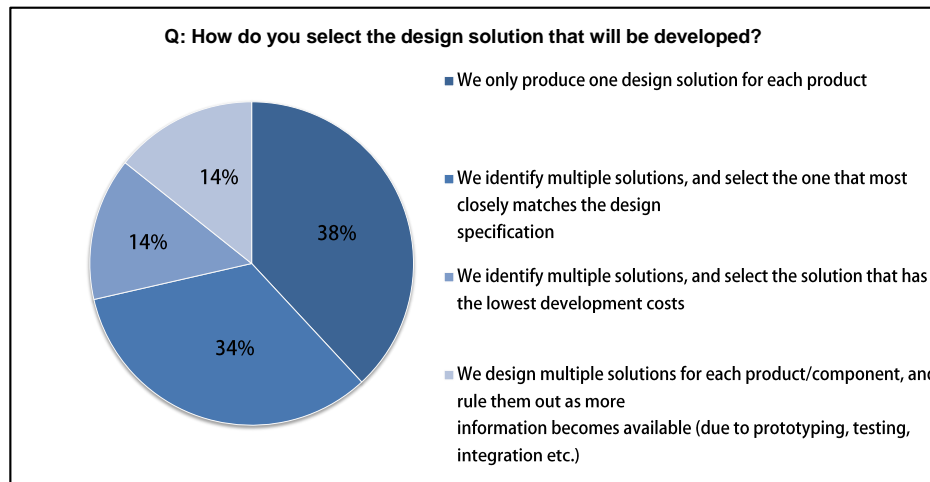


Figure 5.2: Consideration of alternatives and selection.

### 5.2.2.2 Design knowledge capturing and reusing

Almost all the companies interviewed recognize the importance of capturing, documenting and reusing proven knowledge to support decision making in design and development process. The issue is not only the recognition, but also on the practice. Do companies practice effective knowledge management in design? Do

they have effective mechanisms that enable them to capture, represent and share design knowledge in their practice? These are the questions that can clearly show the existence of SBCE enablers in industries.

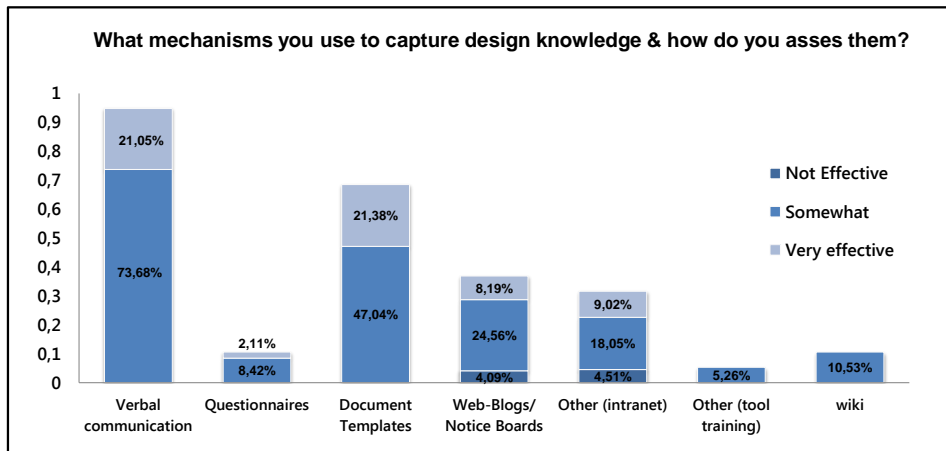


Figure 5.3: Mechanisms to capture knowledge in design.

Looking at Figure 5.3, it is clear that majority of the industries use verbal communication to identify, capture, share design knowledge. Obviously, informal or formal verbal communication is important in PD, however, it has considerable limitations to be used in SBCE process. The limit of depending solely on verbal (formal or informal) communication is on its effectiveness. Recalling the discussions in previous chapters, SBCE uses limit curves, trade-off curves and checklists for communication, convergence and knowledge capturing. These mechanisms are much more effective than verbal communications in many ways (von Hippel and Tyre 1994; Watkin and Clark 1999; Thomke 2000). In fact, in our survey, respondents stressed this fact and said, 80% of the mistakes could have been prevented at the right time if information is pulled from previous projects. Design knowledge should be accessible to be reused. However, verbal communication is not an effective way through which design knowledge and information to be documented and provisioned.

In Figure 5.4, the current challenge in knowledge capturing among the surveyed companies are reported, which validates the discussion about the ineffectiveness of the current practice of LLD (lesson learned document) for knowledge capturing and provision. As shown in the figure, designers find it difficult to extract information and knowledge from previous projects, often consumes considerable time to look for usable information, and there is incompatibilities between knowledge formats. Thus, industries will be challenged to implement SBCE without the necessary formalized and effective mechanisms to identify/capture/document design problems, solutions and knowledge. Moreover, industries will have challenges to make a continuum of knowledge flow among teams and between projects to enable SBCE.



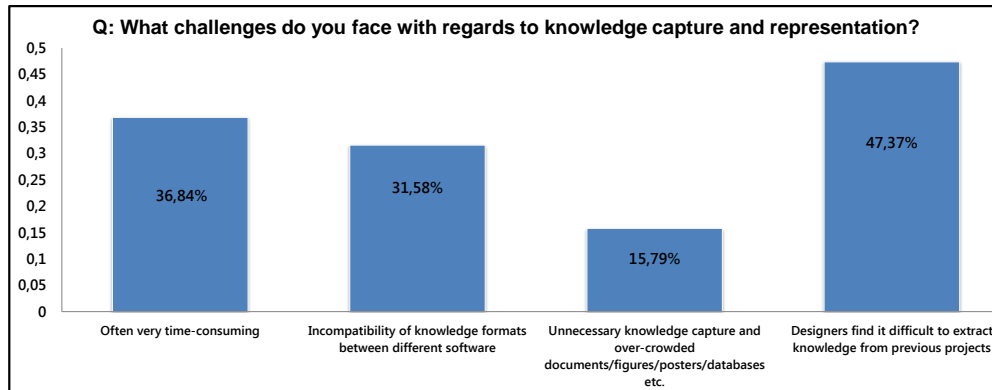


Figure 5.4: Challenges in knowledge capturing and representations.

### 5.2.3 Research objective and methodologies followed

In summary, SBCE is gaining interest from the industries, and international initiatives are emerging to integrate the principles and practices of SBCE in PD process. However, both previous researches and the field study suggest the current adoption level in industries towards SBCE is very low. That is, there is a lack of understanding on how to explore design alternative sets, on how to communicate about them, how to reuse previous knowledge to eliminate inferior alternatives using the mechanism such as trade-off curves, limit curves and checklists.

The main research gap about industrial awareness, the research objective and the research methodologies followed are summarized in Table 5.2. In this part of the thesis the objective is to develop a learning method and validated its effectiveness in an industry. The methodologies followed to design the learning method and the validation methodologies followed are explained below.

- *Methodology followed to design a learning method*

In order to develop a learning method a serious gaming (SG) approach is used. The learning method is called SBCE serious game (SBCE SG) which is aimed at introducing the principles and enablers of SBCE in a simple and engaging manner to increase the awareness level in industries.

Serious games can be defined as ‘the application of games which are aimed at education and learning’ (Wouters, et al. 2007). There are six characteristics that make a serious game as an effective approach to introduce new and complex concepts as SBCE: (1) *internalize knowledge without interfering in an actual practices*, SGs put boundaries between actions in a game and consequences in reality, but players acquire new skills and knowledge transferable to actual practices (Prensky, 2001); (2) *improve communication*, gaming creates a means to support effective communication and structures debates between teams (Geurts and Joldersam, 2001); (3) *create consensus*, beyond communication gaming creates means to reach consensus, conflict mediation and

collaboration between actors' perception about a subject matter (Duke and Geurts, 2004); (4) *commitment to action*, gaming is used to introduce and test new concepts, to convince industrial players on the need for intervention, to introduce approaches to the intervention, and to introduce the roles of the participants in the intervention process (Mayer, 2009); (5) *stimulate creativity*, gaming lets player to leave behind their routines, provide settings to experiment new ideas and research the challenges in it (Duke and Geurts, 2004); (6) *simulate complexity*, reality is much more complex than any attribution in gaming, however, games help to simplify acceptable level of complexity to educate players on how to respond on complex problems (Duke and Geurts, 2004). Such characteristics and opportunities are rare in traditional methods such as lectures based on handouts (which are normally ineffective in giving hand-on experiences) or case studies (which lack in giving feedbacks before actual implementation). That is why serious game is used as a method to develop the learning method for SBCE.

Table 5.2: Research gap-one, objective and research methodologies followed/used.

Research gap-one	Objective	Research methodologies followed/used	
		Methodology to design a learning method	Methodology to validate the learning method (SBCE SG)
There is a growing interest in industries in adopting SBCE but there is low level of awareness in practice.	Develop a learning method to introduce SBCE principles and enablers to practitioners.	Serious gaming approach is used to develop a learning method called SBCE serious game (SBCE SG). The principles and enablers of SBCE are embedded into the game.	Structured questionnaire based on Garris, et al. (2002) framework is designed to measure the learning outcomes of playing SBCE SG in an industry. Moreover, descriptive and inferential statistics are used to infer the implications for practice and theory.

- *Methodology used to validate the learning method (SBCE SG)*

After the SBCE SG is designed, validation of its effectiveness is measured. A structured questionnaire based on Garris et al. (2002) framework is developed. This framework is the most prevalent framework in measuring the learning outcomes or effectiveness of a serious game. The framework divide learning aspects of games into three: *declarative learning*, which is concerned with the effectiveness of a game in transferring the underlying theories embedded in the game; *procedural learning*, which deals with the measurement of the abilities of players in understanding complex patterns embedded in the game; and *strategic learning*, which measures the intellectual abilities and willingness of players to adopt what is though in the game to real-life problems.

The questionnaire contains 26 questions grouped in the three learning aspects. The questions are formatted in Likert five scale scheme (Likert 1932).

The game has been played by 60 highly experienced engineers and managers working in Carel Industries<sup>13</sup> ([www.carel.com](http://www.carel.com)). The company is developing products for HAVC/R market. Validating the game in this company enables the thesis to reflect the applicability of SBCE in smaller companies, which is in different context than SBCE's origin (big OEMs). After playing the game in the company, it has been possible to measure the learning outcomes using the questionnaire provided. Using appropriate descriptive and inferential statistics, the effectiveness of the game has been measured. Moreover, interesting insights are gained concerning the perceived advantages of SBCE in this particular industrial context and the practical hurdles that engineers/managers anticipate in adopting it in reality (refer to chapter 6 for details of the SBCE serious game design and validations).

### 5.3 Research gap two – Lack for a systematic methodology for identifying and prioritizing areas to apply SBCE

The second part of the thesis is concerned with SBCE implementation for a product. That is particularly related to the question on how to identify and prioritize areas where SBCE brings its utmost benefit. This argument states that a product is composed of several sub-systems and components, but, all will not have the same importance for SBCE implementation. For clarity, Figure 5.5 shows the research questions schematically.

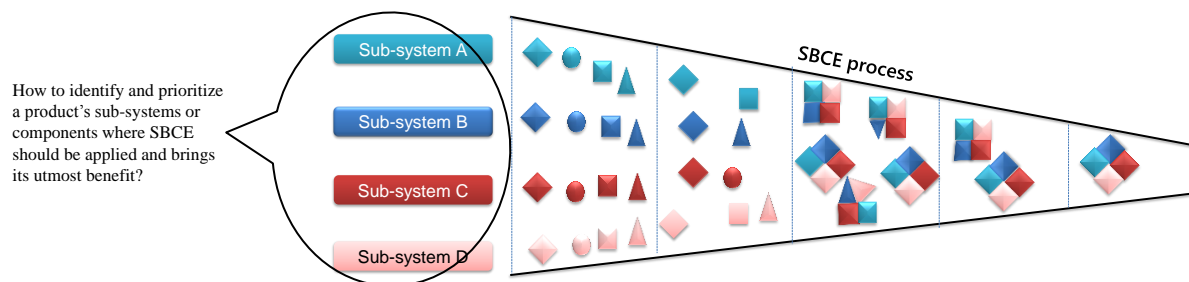


Figure 5.5: Research question on how to identify and prioritise areas for SBCE implementation.

The argument that rationalizes the methodological gap is the extensive nature of SBCE. To conduct an SBCE process, designers should go through extensive phases (exploration of alternative sets, communication of alternative sets, test of alternative sets and converge to optimal sets). Doing all these requires considerable time,

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<sup>13</sup> This company is listed  $\neq 1$  in Table 5.1. The company has shown a high maturity level in applying lean initiatives compared to the other industries that are surveyed. Moreover, the company has shown commitment to play the game and further apply SBCE in their product portfolios.

investment and capabilities. For example, Terwiesch et al. (2002) and Bogus (2005) underscored the extensive nature of SBCE strategy, and asserted that it should be used when the cost of pursuing it is cheaper than to the value it can create. Ford and Sobek (2005) also proposed a real option model to find optimal number of sets to consider; limiting the efforts needed to conduct SBCE. Thus, SBCE's adoption should not be based on a random choice, and there is not a guarantee that any such initiative will be a success (Raudberge 2010, pp. 690). In particular, the technological capabilities and methodological readiness and resources availability to fasten SBCE process are scarce in many industries such as small and medium sized ones (Raudberge 2010; Rossi, et al. 2011/b). In these situations, companies need to focus their efforts on areas of improvement where SBCE will bring its utmost benefits. Therefore, there is a need for a systematic methodology to identify and prioritize subsystems or components a priori of pursuing such an extensive process. Otherwise, efforts made will be wasted without achieving the desired value. This thesis proposes such a methodology called SBCE IR that enables to breakdown design problems and derive rules of prioritization for SBCE implementation. In this regard, the SBCE IR promotes incremental SBCE implementation at subsystem or component levels rather than full system level innovation.

### **5.3.1 Research objective and methodologies followed**

The summary of the research gap, the objective and the research methodologies followed are presented in Table 5.3.

In this part of the thesis, the main objective is to develop a methodology called SBCE innovation roadmap (SBCE IR) that is used as a guideline to be used by designers to identify and prioritize areas where SBCE should be applied. The methodologies followed to build the SBCE IR methodology and the methodologies used to validate SBCE IR are explained below.

- *Methodology followed to develop SBCE IR methodology*

The methodology followed to build SBCE IR follows two steps. First, criteria and related assumptions that are required to build the SBCE IR have been defined. Second, existing methods and tools that are needed to execute the steps of SBCE IR are identified. The following criteria and assumptions are considered:

- (a) *The process of overcoming contradictions will follow SBCE process, SBCE IR methodology is constructed based on the assumption that identification and overcoming of contradictions lead to design improvements. The assumption is based on the prominent theory of innovation called TRIZ which is introduced in 4.6.2. TRIZ claims that overcoming contradictions lead to genuine innovations and it provides ways to arrive to design solutions (Altshuller 1984). SBCE IR takes the synergies between TRIZ and SBCE process. Thus, TRIZ's concept of contradiction enables SBCE*

IR to identify improvement areas, where as SBCE’s principles will follow to overcome the contradictions by exploring design solutions, communicating solutions to team members and finally converging to an optimal final design concept. That means, contradictions will be input to begin SBCE processes.

(b) *The area of improvements should be valuable for customers:* there could be several contradictions in a product system. However, all contradictions will not have same importance. Once contradictions are identified evaluating them for customer importance is taken as a criterion (i.e. how important it is for customers to overcome a contradiction?).

Table 5.3: Research gap-two, research objective and research methodologies followed/used.

Research gap-two	Objective	Research methodologies followed	
		Methodology to develop the SBCE IR methodology	Methodologies to validate the SBCE IR methodology
There is no systematic methodology to identify and prioritize areas (sub-systems or components) for SBCE implementation. That is, answering on how to identify and prioritize intervention areas where SBCE can be implemented, and as a consequence it is possible to enhance innovation that maximize customer satisfactions and achieve competitive advantages.	To develop a systematic methodology to identify and prioritize areas for SBCE implementation. The methodology developed is called SBCE Innovation Roadmap (SBCE IR).	<ol style="list-style-type: none"> <li>1) Criteria and related assumptions are defined to build SBCE IR.</li> <li>2) Existing methods and tools that are needed to execute the steps of SBCE IR are identified.</li> </ol>	<ol style="list-style-type: none"> <li>1) Case study on AHS system</li> <li>2) SBCE process in Rack subsystem</li> <li>3) Open questionnaire to assess SBCE IR by experts.</li> </ol>

(c) *The area of improvements should give competitive advantages:* in addition to taking customer importance as one criterion to prioritize contradictions, a competitive advantage is also taken as another criterion (i.e. how much competitive advantage a company would get by overcoming a contradiction?). This criterion is needed since customer importance is not always the only source that can be used to identify design improvements. Thus, analyzing competitors’ products should also be used as one criterion to prioritize contradictions while building SBCE IR for a product.

(d) *The area of improvements should be achievable with respect to the resources available:* this is an optional criterion to build SBCE IR. However, it is very important to consider. Since overcoming

different contradictions require different levels of resources or efforts, designers should balance the importance of overcoming contradiction with respect to the resources/capabilities available in a company.

Once the criteria and assumptions are defined SBCE IR is built on six steps. To facilitate the steps common tools and methods are used to facilitate each step (see chapter 7 and section 7.2).

- *Methodologies used to validate the SBCE IR methodology*

Once the steps of the SBCE IR are defined and the necessary tools and methods are identified, three validations are conducted. Firstly, a case study on Adiabatic Humidification System (AHS)<sup>14</sup> is conducted to test the methodology. Secondly, using the SBCE IR constructed for AHS system a subsystem called Rack<sup>15</sup> is chosen to further experiment on how to start an SBCE and to improve the current Rack design. The SBCE process conducted in the subsystem shows promising cost reductions for new Rack design.

Thirdly, pros and cons of the SBCE IR have been assessed by conducting interviews with designers and project managers involved in the case study for AHS. An open questionnaire is provided to evaluate the advantages, limitations and applicability of SBCE IR in the company. Interviews are made with four experts in the company who are well experienced and have technical, managerial and market competences (refer to chapter 7 for details of SBCE IR methodology and the validations).

## 5.4 Conclusions

The purpose of this chapter was to set the gaps that this thesis is addressing, the research objectives and the methodologies followed to answer the gaps.

To summarize, two gaps are identified: (1) there is a low level of awareness in industries about SBCE's principles and enablers, and (2) there is a lack of methodological approach that is used to systematically identify and prioritize areas for SBCE implementation at a product level.

The first gap is taken as an import issues to address. Since there is a growing interest in SBCE across industries developing a learning method to bring a hand on-experience is considered paramount. A serious gaming approach is used to design SBCE serious game to introduce practitioners about SBCE. The game will help to industries to experiment SBCE in a simulated environment before adopting SBCE in real practice, and can identify the benefits and hurdles of adopting SBCE. Moreover, a questionnaire is developed to

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<sup>14</sup> This case study on AHS has been conducted in the same company the SBCE serious game has run ([www.carel.com](http://www.carel.com)).

<sup>15</sup> Rack is a subsystem of AHS used to distribute water to an ambient (refer section 7.3.2 for details).

validate the effectiveness of the game. The game has been played in Carel Industries and feedbacks are collected.

The second gap is related to the identification of improvement areas where SBCE should be applied to obtain innovation. SBCE is an extensive process and a systematic methodology is required to help designers to identify, prioritize and plan SBCE implementations. This thesis proposes such a methodology called SBCE IR. Before building it, criteria and assumptions are identified and steps are defined. Moreover, existing and common tools/methods are identified to facilitate the steps. The SBCE IR methodology is tested in a case product called AHS. A Rack subsystem is selected to conduct an SBCE process as a validation way on how to use the roadmap to improve a Rack design. Finally, to validate the advantages, applicability and limitations of SBCE IR, an open questionnaire is developed and interviews are made with AHS experts.

Chapter 6 is dedicated to PART I of this thesis where the detail discussions on the SBCE serious game are provided. In this chapter the validation of this learning method in industry is also presented in-depth. Chapter 7 on the other hand is dedicated to PART II of this thesis. There, the SBCE IR methodology developed in this thesis is discussed in detail. Moreover, in chapter 7 the details are presented on the validation process of the methodology in the AHS case. For a reminder, the structure of the thesis is reshown in Figure 5.6.

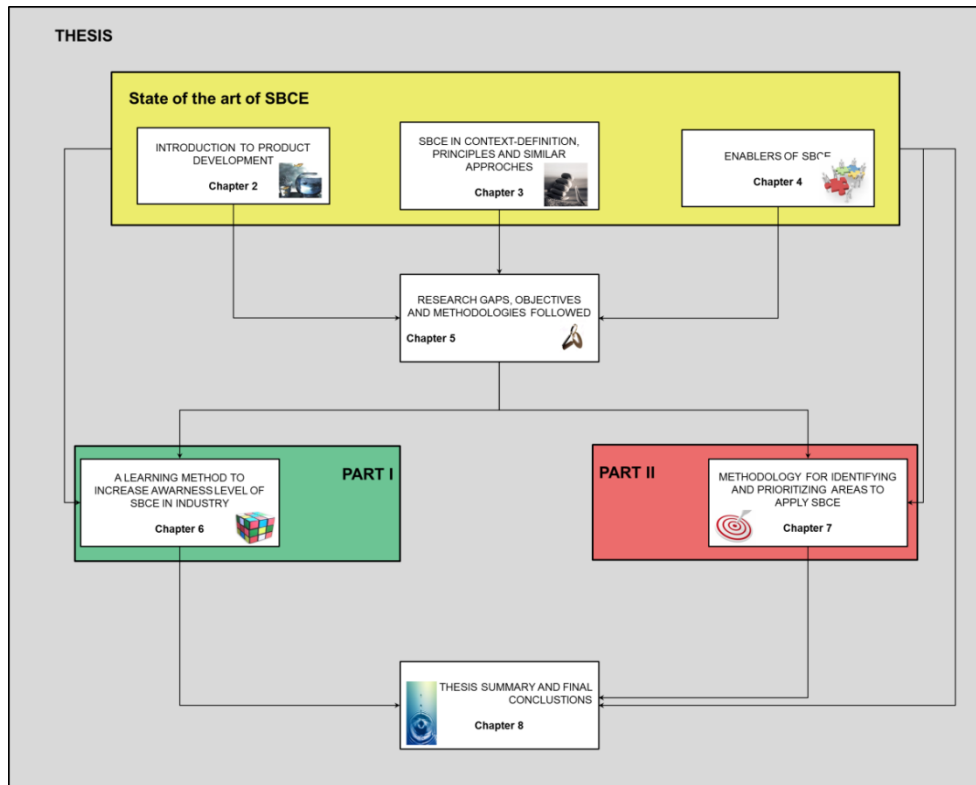


Figure 5.6: Structure of the thesis.



## **6 A LEARNING METHOD TO INCREASE AWARENESS LEVEL OF SBCE IN INDUSTRY**

To address the limited awareness across industries, a learning method for SBCE has been developed which is called SBCE serious game (SBCE SG). The game is designed to bring a hand-on experience about SBCE, in an engaging and educative manner. Gaming is gaining wider attention to introduce new concepts to industries or practitioners. It separates players from the real word scenario and immerses them into a simulated environment. Before going into real implementation, games can offer opportunities for industries to experiment complex models and concepts in simulated environments. This characteristic makes games or serious games effective way to increase the understanding level of a theory, and then practitioners can anticipate the benefits and difficulties of applying that particular concept in reality. Moreover, games facilitate discussions among players or team of experts to arrive into consensus among them. In this way, during real implementation phase, players will have better ideas on their roles and will participate in a change process effectively. Such opportunities are rare in traditional methods such as lectures based on handouts (which are normally ineffective in giving hand-on experiences) or case studies (which lack in giving feedbacks before actual implementation). That is why in this thesis serious game is taken as method to develop the learning method for SBCE, and eventually improve the effectiveness of the learning outcomes.

The game has been validated through playing the game in Carel Industries with 60 engineers and managers who are designing new products for HVACR (Heating, Ventilation, Air-Conditioning and Refrigeration) market. The general contributions obtained for the industry are: the game increases the understanding of SBCE, educate designers/managers on how SBCE can be applied, and identifying the pros and cons of adopting SBCE in practice. For the theory, it has been possible to drive some theoretical implications through measuring the learning outcomes of the serious game and reflect on its applicability in this particular industrial context.



## 6.1 Introduction

In this section of this chapter (section 6.1.1), an introduction about SG is given by reviewing the state of the art of serious gaming and existing games in concurrent engineering. In section 6.1.2, introduction about the SBCE serious game will be presented. The introduction addresses the framework, inputs and stages of the SBCE game. In section 6.3, the validation and measurement of the learning outcomes gained in the game play are discussed. Finally, section 6.4 deals with summarizing the chapter, laying out the limitations of the research and propose future possible researches.

### 6.1.1 State of the art of serious gaming

“Game” can cover variety of activities and its definition strongly depends on the authors’ perspective of a game. Serious game (SG) is still not a well-defined term and there are some related and similar terms in the literature such as “Simulation game”, “Game Based Learning”, “Educational game” and “Edutainment”. In general, the application of games which are aimed at education and learning can be defined as “Serious Games” (Wouters, et al. 2007). It is defined by some researchers as an activity whose main purpose is learning serious contexts through playing (Zyda 2005; Charsky 2010). Learning and education via games are the main objectives rather than pure entertainment in SGs (Egenfeldt 2006).

Although a generally accepted definition of games does not exist. Below, there are two definitions of games that characterize games in general, provided by Klabbers (2006/b) and Juul (2005). These definitions have several characteristics in common. They both describe rules, outcomes and players as game elements. Juul further emphasizes the emotional attachment of the players with the outcome. Klabbers emphasizes the competition element, caused by constraints and resources.

*“Games are rule based systems with variable and quantifiable outcomes, in which different outcomes are assigned to different values, the player exerts an effort in order to influence the outcome, the player feels attached to the outcome, and the consequences of the activity are optional and negotiable”*

*(Juul 2005)*

*A game is a form of play. It is an activity involving one or more players who assume roles while trying to achieve a goal. Rules determine what the players are permitted to do, or define constraints on allowable actions, which impact the available resources and therefore influence the state of the game space. Games deal with well a defined subject matter (content and context)*

*(Klabbers 2006/b)*

An important element of games is that they are separated from the *real world*. There is a permeable boundary, the so called ‘magic circle’, which separates the game world from reality (Copier 2007; Klabbers 2006/b; Prensky 2001; Armstrong and Hobson 1975; Crawford 1984). Within this boundary, the rules and

roles in the game are valid and the outcomes of the activities within this boundary do not have consequences for the real world. On the other hand, this boundary is open to transfers between game and reality. Recently, Copier (2007) concluded in her dissertation that the influence and networks surrounding games go beyond the magic circle. Game play is influenced by the cultural and social backgrounds of the players, and players acquire new knowledge and skills which can be used in reality. Apart from the separation of reality, there are five key characteristics of a game that makes it valid method to introduce new concepts (Duke and Geurts 2004), as of SBCE process to an industry. They are:

- *Improving communication*: communication between actors in PD processes is important. Gaming creates a setting in which multiple stakeholders involved in designing and managing products can communicate. Gaming is a valuable method for supporting the communication and learning processes and structuring the debate between stakeholders (Geurts and Joldersma 2001).
- *Need for consensus*: Duke and Geurts (2004) describe three perspectives beyond improving communication: reaching consensus, conflict mediation and collaboration. A game can explore whether or to what extent a conflict between actors' perceptions exists. By learning from the perceptions of other stakeholders, the proposed solutions can be considered from multiple perspectives.
- *Commitment to action*: gaming can be used to introduce or test new process or implementation, to convince the designers and managers on the need for the intervention, to introduce the intervention approach, and to show the roles of the participants in the implementation process (Mayer 2009).
- *Stimulating creativity*: games can be considered as a laboratory for developing and practicing new concepts. By stepping into a game setting, players leave behind their routines. This new environment encourages creativity. In addition to experimenting with routine processes and researching future development, games are used in researching difficult or new situations (Duke and Geurts 2004).
- *Understanding complexity*: reality is much more complex than any attribution in a game. The reality in design process involves problems in dynamic environments, with many variables and actors; these actors have different objectives and values, and the outcomes are uncertain and unpredictable. The objective is to use serious games to gain a holistic view of a system (Duke and Geurts 2004).

In sum, games offer ways to internalize knowledge in safer environments, and are useful to train problem solving skills and track own performances (Kolb and Fry 1975; Kolb 1984). In SGs, participants will have the possibility to experience the consequences of their decision and behavior. Further, they gain new skills without fearing that they may cause any damage to their company. According to knight (2002), organizational learning, and thereby improving the innovation potential follows a cyclic pattern as shown Figure 6.1. To facilitate innovation, adopting the right learning method is paramount. Serious games have

been used to educate practitioners to introduce new concepts that support improvements in one working environment (Raybourn, et al. 2005; Takeuchi and Nonaka 1986). Well-designed SGs provide the opportunity for experiential learning and provide an environment for active and critical thinking. Experiential learning opportunities enable game players to learn from contextual information embedded in the dynamics of a game, and through the risks, benefits, costs, outcomes and rewards of alternative strategies that are undertaken in a game play (Raybourn, et al. 2005; Daley, et al. 2007). Experiences in a game will positively influence perceptions of a subject-matter and increase interests in portrayed areas.

These characteristics of gaming make it a good candidate to introduce SBCE in which its principles and enablers are not well understood and practice in industries. Game helps to separate the interference with real practice, and designers and managers can experiment and understand the concepts of SBCE before a real implementation. Then, reflections can be made on what sort of benefits and difficulties can a company faces during SBCE implementation. Thus, gaming can be used as the first step in a change process, to introduce and build consciousness about the principles and practices of SBCE among designers and managers.

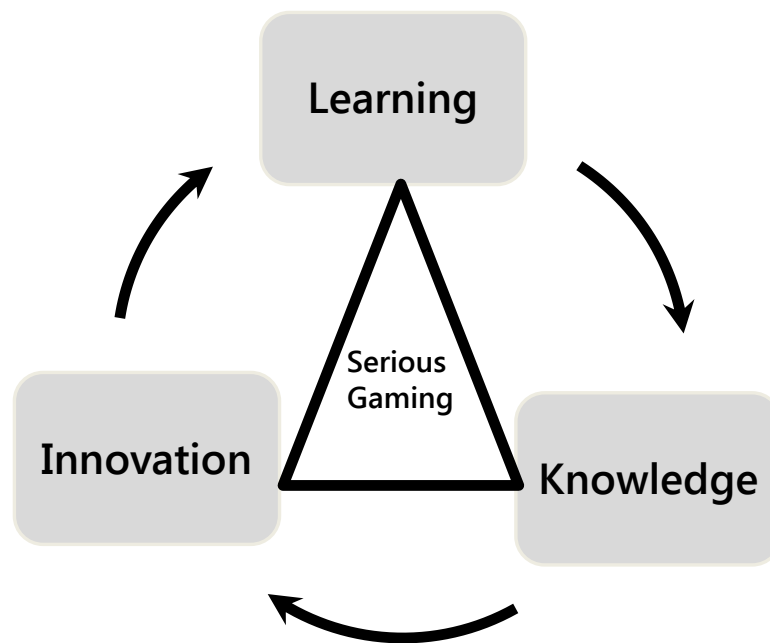


Figure 6.1: Learning and innovation cycle (adopted from Knight 2002).

### **6.1.2 Existing serious games in concurrent engineering**

The nature of PD makes it an ideal process for serious games applications (Pourabdollahian, et al. 2012). Product development process, as mentioned earlier, involves interrelated and complex decision making activities. Product developers should make decisions under imprecise and uncertain information which might not be known before wasting time and spending extra costs. Moreover, it involves several stakeholders such

as customers, designers, manufacturers, and suppliers which make PD difficult to model for process improvement. Gaming supports the innovation cycle shown in Figure 6.1 by providing a learning instrument to introduce new concepts, and increase the awareness levels of participants in a changing environment.

In this section, some of the existing SGs that are found from previous works are briefly reviewed, and they are compared with the SBCE SG in terms of their contents compared to what is embedded inside SBCE game.

According to PRIME project report (PRIME 2006), there are three identified games that have been developed to support players to understand specific challenges of developing new products, support them in understanding concepts of concurrent engineering (CE) such as team work, parallel tasking/scheduling, communication, collaboration and etc. These games are: COSIGA, GLOTRAIN and CITY CAR.

“COSIGA” is an internet based computer simulation game developed by Nottingham University in collaboration with other partners under an EU funded project (Pawar 1995; COSIGA 1997; Riedel, et al. 2001; Riedel 2007). In COSIGA, game players learn about CE and communication skills in a distributed development team context. This role simulation game is trainer led and simulates the PD processes in a virtually simulated enterprise in different scenarios. Five players representing project manager, marketing manager, designer, production manager, and purchasing manager are located at disperse locations and follow specific roles in a simulated company to interact using their individualized client interface to communicate and collaborate. The design process in the game includes drawing up a market specification, a product specification, designing a truck, and allocating production processes. The product's manufacturability is tested in a simulated factory to produce final products. In order to win, the players have to work together effectively with others to deliver a truck faster, within specification and budget. During the game, players experience direct feedback as a result of their actions which accelerates their learning (Riedel, et al. 2001; Riedel, et al. 2007).

“GLOTRAIN” is another computer and reality simulation game addresses different organizational forms of PD and production (Hoheisel, et al. 2000). Within one scenario, it simulates the development and the production of a product in a distributed work setting. The players improve their communication skills, their collaborative skills as well as the related ICT skills.

“CITY CAR” simulation game addresses PD and project management (Goffin and Mitchell 2006). The players undergo the board based development of a product. During the game, they improve their communication skills and their capacity for teamwork. The CITY CAR simulation game has three modules. The first module simulates the production of a truck in a Taylor organization that is divided into the departments such as procurement, sales, manufacturing and central services. Each player takes over a certain

functional role. The players follow role description to realistically simulate the rigid operations of a purely functional organization. The second module simulates group work and process orientation as the precondition for lean organization. This time, the players are assigned to one of these groups: customer service, manufacturing, manufacturing services and internal services to process tasks in teamwork. The members of a particular group have to organize their intragroup work responsibilities internally to be successful. The third module simulates three autonomous distributed companies with particular key competencies that have to cooperate in order to develop and produce a product. To bridge distance, they use different information and communication technologies. The learners will experience the key characteristics of distributed PD (cooperation, interconnectedness and symbiosis). All three modules are based on each other and tell a coherent story of the development of a model company. Groups of players learn to develop a product from the beginning to the end – from product design and production management up to real production and marketing. The game modules allow to experience and to practice distributed teamwork by the use of modern tools and methods for communication.

There are important differences between SBCE game and the above games. First, the main difference in-between is concerning the objectives. In the previous games, players are aimed to learn about the challenge of communication and sharing of information among team members. However, in SBCE game the objective is expanded. In SBCE game, players are aimed to learn not only the challenge of interpersonal communication and sharing of knowledge but also support players with SBCE enablers. For example, in SBCE game tools such as tradeoff curves, limit curves and checklists are embedded to facilitate players' understanding on the use and importance of the enablers for effective management of knowledge in SBCE process.

Second, SBCE game is designed to educate about set based thinking: exploration of alternative designs, communication between sub-system designs and evaluate the explored solutions to converge into high value alternative. However, the existing games focus on PBCE where the concept of considering large sets at early phase of a design process and its importance is not mediated. Rather in previous games players receive feedback late once decision is made. In this regard, SBCE game advances the learning objective from design-build-test to test-build-design paradigm (refer section 2.2 for the differences). The main differences between previous games and SBCE SG are summarized in Table 6.1. Nevertheless, the previous games and SBCE game can be used as complementary to educate CE concepts. In particular, the previous games have strength in educating soft skills as well as interpersonal communication, team building, lean organization and negotiation aspects which all are needed to achieve lean process in PD. SBCE game can be used to train lean design aspect (i.e. how to develop a high value design concept) following SBCE principles and enabling tools.

Table 6.1: Comparison of existing and SBCE serious games.

Serious games	Objectives and skills covered	Problem solving approaches	Scopes
COSIGA, GLOTRAIN, CITY-CAR	Soft skills for communication, information sharing in concurrent engineering environment	<i>design-build-test</i>	Detail design/development, production, marketing
SBCE	Introduce how sets of alternatives are explored, communicated, and evaluated in a knowledge base environment using tools such as tradeoff curves, limit curves, checklists	Both <i>design-build-test</i> and <i>test-build-design</i> in different stages of the game	Early phase of design

## 6.2 Introduction to SBCE serious game

This section is dedicated to discuss in detail about the steps and assumptions made in designing the SBCE game. In the SBCE game, players have to design a simplified airplane structure using different type of LEGO bricks which have points on their tops (as shown in Figure 6.2). The airplane has four sub-systems to be designed by players (cockpit, body, wing and tail). A single point on each brick is assumed to have the characteristics listed in Table 6.2. Moreover, the weight of a passenger should be considering in the design of an airplane structure, and each passenger is assumed to weigh 60 units. The airplane structure is chosen as the game element since it involves several subsystems, where a player in a team represents one of the subsystems. In this way, it creates more “complexities” into the game such as on how to explore subsystems solutions, on how to communicate about subsystem solutions, on how to evaluate sets and converge to optimal solution. Therefore, using the game, educators can effectively educate SBCE with its “complexities”.

Table 6.2: Characteristics of a single point on a LEGO component.

	Cost	Ordering time	Capacity	Weight	Length	Width
Measuring unit	monetary	time	# of passengers	weight	distance	distance
Value	10	0.5	3	100	1	1

### 6.2.1 Framework of SBCE serious game

The game is designed and divided into two stages: Stage one, where players design an airplane for a given list of customer requirements following PBCE process. In Stage two, players are provided with the necessary enablers of SBCE to simulate an environment where designers presuming to design an airplane structure

following SBCE process. The enablers will help players to explore alternative design concepts, communicate about alternative solutions within a team, and converge into a preferred (a high value) airplane structure. After each stage, players' performances' breakdown in terms of cost and time of development will be provided to facilitate discussions. The game is played in a team of four players and each player in a team represents a sub-system department (body, wing, cockpit and tail). The general framework of the game design is presented in Figure 6.3. The discussions on inputs, the stages and the associated steps of the game are elaborated in the following subsections.

### 6.2.2 Inputs to SBCE serious game

The main inputs to the stage one of the game are customer requirements (Table 6.3) and supplier components catalogue (right side of Figure 6.2).

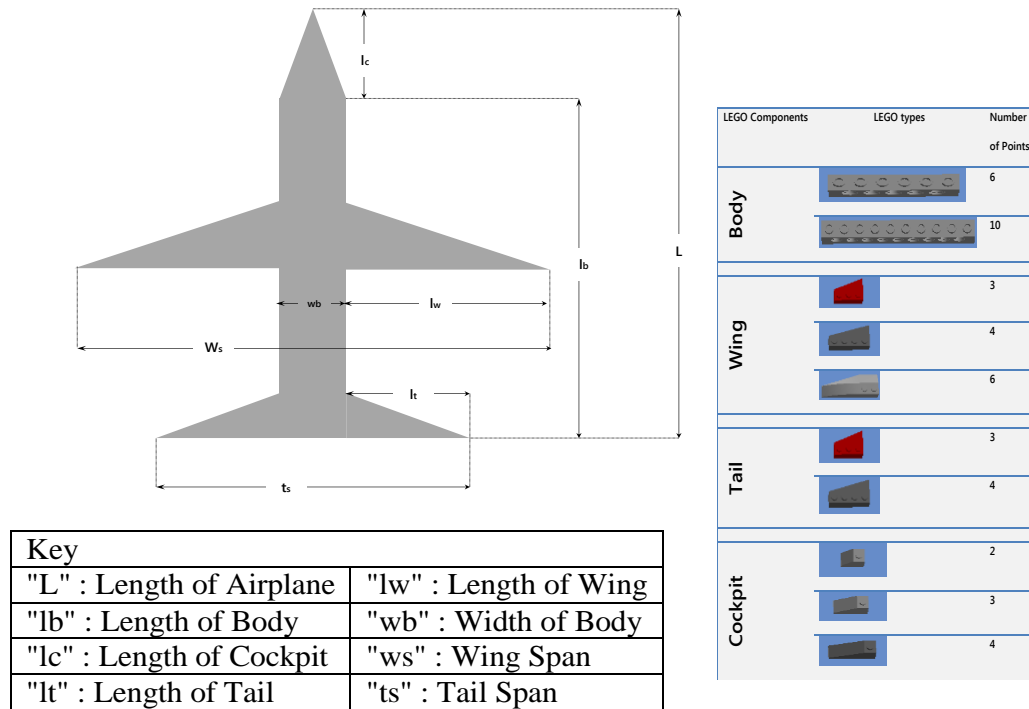


Figure 6.2: A simplified airplane structure to be designed and the LEGO bricks used.

In the game, there are five customer requirements: number of passengers ( $N_p$ ); airplane weight ( $W$ ), which is the sum of weight of the airplane structure ( $W_a$ ) and the total passengers' weight ( $W_p$ ); length of airplane ( $L$ ); wing-span ( $w_s$ ) and tail-span ( $t_s$ ). Each team will receive different lists of the requirements, and act as a 'company' that develops an airplane structure for a particular customer. The customer requirements to build an airplane structure were made intentionally to be imprecise. For example, the  $N_p$  might be from 91 to 120 and the wing-span could be 7 to 20 (see customer requirement for group 1 in Table 6.3). This is made to

reflect the reality, in which customers often suggest imprecise information, and force designers to explore their concept solutions wide open.

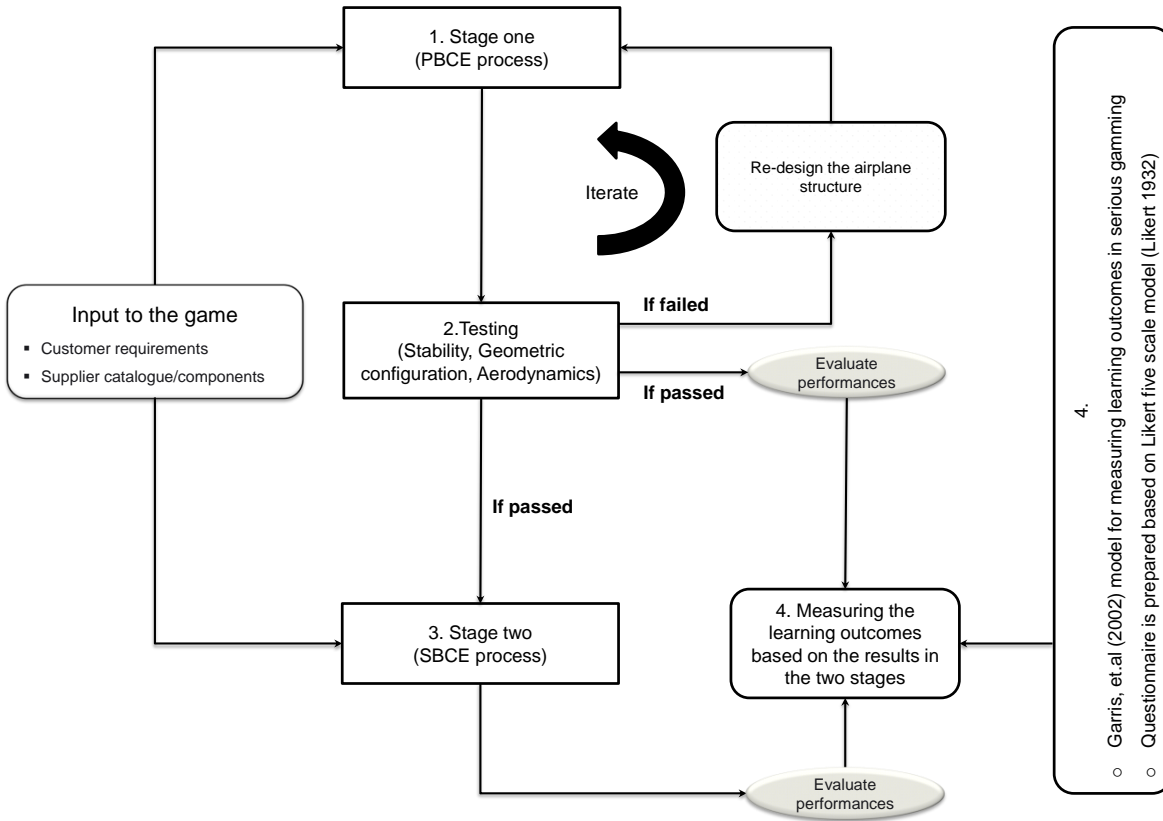


Figure 6.3: Framework of SBCE serious game.

In the game, these requirements can be handled in different ways in the stage one (PBCE process) and in stage two (SBCE process). Thus, players will understand the advantages of following SBCE than PBCE process to better achieve the customer requirements. For example, while playing stage one a player representing body department in group 1 might consider number of passengers as 100 (somewhere between 91 and 110) to determine the body size. This is exactly what point based engineering is; freezing requirements early in the beginning without understanding if freezing the requirement is worth pursuing (Ward, et al. 1995), and players quickly decide on how many passengers should be in the airplane they going to design.

The problems of following point based approach are many. For example, once players start designing an airplane with number of passengers as 100, they have to test the design if it passes constraints from “testing department”. Fixing the number of passengers means fixing other design decisions such as the weight of the airplane. The weight of an airplane will fix the decision about the capability of the design to fly or being stable during flight. Thus, there is no reason why designers pick a single point from all the possible points in



the design space without being sure of passing the constraints arising from downstream functions. However, this is what often happens in practice (Rossi, et al. 2011/b). Often design rework-loops start late in the process once infeasibilities are revealed and when there are little chances to make inexpensive fixes.

Table 6.3: List of customer requirements in SBCE serious game for 8 groups.

Group 1			Group 4			Group 7		
Customer Requirements			Customer Requirements			Customer Requirements		
Ranges	Min	Max	Ranges	Min	Max	Ranges	Min	Max
Number of Passengers	91	110	Number of Passengers	70	120	Number of Passengers	140	170
Length of Airplane	10	22	Length of Airplane	11	20	Length of Airplane	18	27
Weight of Airplane	9500	14500	Weight of Airplane	8000	14000	Weight of Airplane	15000	21000
Wing Span	7	20	Wing Span	9	17	Wing Span	17	28
Tail Span	7	15	Tail Span	7	14	Tail Span	17	22

Group 2			Group 5			Group 8		
Customer Requirements			Customer Requirements			Customer Requirements		
Ranges	Min	Max	Ranges	Min	Max	Ranges	Min	Max
Number of Passengers	30	80	Number of Passengers	100	130	Number of Passengers	170	200
Length of Airplane	8	15	Length of Airplane	12	24	Length of Airplane	22	34
Weight of Airplane	5000	10000	Weight of Airplane	10000	17000	Weight of Airplane	18000	25000
Wing Span	7	12	Wing Span	10	22	Wing Span	19	30
Tail Span	6	10	Tail Span	10	17	Tail Span	19	25

Group 3			Group 6		
Customer Requirements			Customer Requirements		
Ranges	Min	Max	Ranges	Min	Max
Number of Passengers	50	100	Number of Passengers	120	150
Length of Airplane	9	17	Length of Airplane	15	25
Weight of Airplane	6000	11000	Weight of Airplane	13000	18000
Wing Span	8	15	Wing Span	13	25
Tail Span	6	12	Tail Span	13	20

Whenever customers are not precise enough to start a design activity, designers have to take into account the situation into two ways in SBCE. First, as Toyota practices, engineers should do ethnographical or similar studies to understand customer requirements closely (Morgan and Liker 2006). Then, designers can start designing a product with more accurate customer information. Second, as Terwarch et al. (2002) stated, pursuing alternative solutions is another way to proceed with imprecise customer information. The second strategy is embedded in stage two of SBCE game. That is, players consider range of customer requirements and define alternative designs to satisfy the possible requirements. Then, they can progressively eliminate design solutions which are incompatible and infeasible using information obtained from other departments and downstream functions (e.g. testing department).

### 6.2.3 Stage-one of SBCE serious game

After players are given the customer requirements and the supplier catalogue, they start the first stage of the game. This stage is designed to simulate the traditional approach of PBCE. Each team will be allowed the

same time duration (about 2 and 1/2 hours) to provide a prototype airplane structure to testing department. Team members represent different departments divided into the subsystems of the airplane structure as shown in Figure 6.4.

In this stage, there are no supporting SBCE enablers introduced. Rather, designers are grouped into teams and given a list of customer requirements randomly picked from any of the requirements lists from Table 6.3. During this stage, players have to pursue the design process by themselves. This is done purposefully. The SBCE game is targeted to practitioners, therefore, whenever they are given the list of the customer requirements they immediately reflect the way they normally design products in their real job. Thus, during the second stage the “Aha effect” will be produced (Wills, et al. 2006). Creating the “Aha effect” in players’ mind is necessary to educate different ways of designing a product, compared to what they used to do. In fact, most of the designers and managers who played the game never heard about SBCE. Therefore, in first stage of SBCE game, designers and managers are left to design their airplane without interfering how they are going to design the airplane structure.

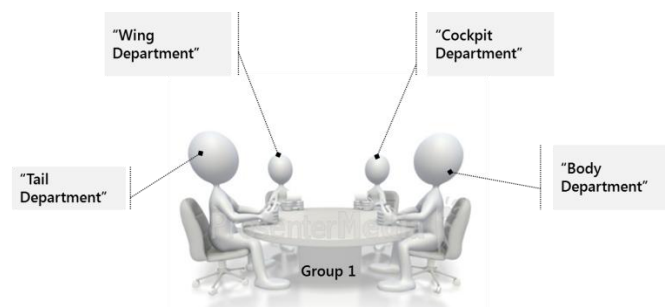


Figure 6.4: Team building in stage-one of SBCE serious game.

Before teams of players start playing the game, they will be assigned numbers that represent the customer groups they going to serve. The game can be played by eight teams representing different companies that are competing to finish airplane structures within the given play duration. At this stage of the game, there is no introduction about SBCE. Players design the airplane based on their own previous experience. Once the game started, team members are allowed to discuss about customer requirements, to make decisions on design specifications and to order LEGO component from the “supplier” (the facilitators presume as the supplier in the game).

#### **6.2.4 Testing in stage-one of SBCE serious game**

Once a team finishes designing and building activities, they bring their prototype design to “testing department”. The facilitator of the game acts as a testing department. Fictitious constraints designed for the purpose of the game are listed in Table 6.4.

Table 6.4: Fictitious testing constrains for SBCE game.

	<b>Constraints type</b>	<b>Constraints equation</b>
1	Geometric configuration	$\frac{2}{3}L \leq w_s \leq L$
2	Ratio of weight ( $R_w$ )	$R_w = \frac{W_p}{W_a} < 1.25$ <p>Where, <math>W_a</math> is the weight of an airplane structure and <math>W_p</math> is the total weight of the passengers in an airplane. Each passenger is assumed to be 60 units of weight.</p>
3	Airplane stability	$l_t < l_w$
4	Alignment between body and cockpit	$l_c = w_b$

Players will not be given the testing constraints at the start of the game. The reason is that, design constraints are not usually evident during design phase. In a real design practice, there could be two basic reasons why designers might not know constraints from downstream functions, in this case, testing department. The first reason is the lack of communication between design and testing department. Designers might not communicate with testing department about constrains that cause product failures. This phenomenon is reflected in the game too. As a facilitator, players rarely ask about the constraints at the start of stage one. Moreover in practice, geographical dispersions of design teams escalate the communication problems. Several sub-systems and components are designed in different locations, and assembled in another. Brining testing constraints upfront, therefore, will be a challenge for designers. The second and the most critical reason is neither designers nor testing department know the causes of failures before having a testable prototype. Moreover, as Oostewal (2010, pp. 179-183) underlined, the point based practice contribute to this problem. Whenever testing is conducted, most industries use a point based testing approach. That is, they test the design only for specific conditions. Rather, in set based practice, testing should be done for range of conditions to understand the risky regions that a design will possibly fail. The test results might not be used in the current project, but can be used to frontload in subsequent projects and evaluate sets of designs in several working conditions. Therefore, to reflect the above facts in practice, and educate designers about the disadvantage of point based approach, players are not given testing conditions upfront. But, after the first trial, players will be given the fictitious constraints to redesign their airplane (if a design fails to satisfy these constraints in a first trail). A team passes stage one only if these constraints are satisfied otherwise the team continues modifying the design.

### **6.2.5 Performance measurement of players in SBCE serious game**

Once a team of players finishes designing and building a prototype airplane structure, they bring the prototypes to the facilitator who acts as testing department. The facilitator takes the design parameters and

tests if customer requirements and the testing constraints are satisfied. If the design fails, the prototypes should be redesigned. Redesigning has penalty costs and additional time to be penalized. After the first trial the testing constraints will be given to players. If the prototype passes the testing constraints, players will be given the breakdown of their performances in terms of cost and time. The calculations rules of development cost and time are given in Table 6.5 and Table 6.6 respectively.

Table 6.5: Rules to measure total development cost in SBCE serious game.

<b>Total development cost (C)</b>					
$C = \text{cost of components}(cc) + \text{cost of iteration}(ci) + \text{cost of penalty}(cp)$					
Where, $cc = \text{total number of points} \times \text{single point cost}$ , $ci = 30\% \times cc$ (this is an additional cost if a prototype airplane fails to pass testing constraints), and $cp$ is an additional cost if a team fails to meet customer requirements). It is determined based on unsatisfied customer requirements and applying the following rules:					
Unsatisfied customer requirements	$N_p$	$L$	$w_s$	$t_s$	$W$
$c_p$	$30\% \times cc$	$40\% \times cc$	$10\% \times cc$	$5\% \times cc$	$20\% \times cc$
Note that: the calculations are pure assumptions used as rules in the game; they might not reflect the real situation in aircraft development.					

Table 6.6: Rules to measure total development time in SBCE serious game.

<b>Total development time (T)</b>					
$T = \text{total orderning time}(tot) + \text{assembly delivery time}(adt) + \text{iteration time}(it)$					
where, $tot = \text{total number of points} \times \text{single point lead time}$ , $it = 30\% \times tot$ (this is an additional time a team will be penalised if a prototype airplane fails to pass testing constraints, and will be augmented for every iteration made ). Assembly delivery time represents the required time that is needed to assembly the components used to build the airplane, it is determined as $adt = \beta \times tot$ , where $\beta$ is an assembly index and is a function of $l_w$ . It is assumed that the higher the $l_w$ , the lower $\beta$ becomes (i.e., bigger sizes are available in standards and smaller sizes should be assembled to orders). To determine $\beta$ , the following rules are used:					
$l_w$	3	4	6	7	$\geq 8$
$\beta$	0.8	0.7	0.6	0.5	0.4
Note that: playing time (design time) is not considered in the calculation due the fact that players spent considerable amount of time to understand the game itself. Thus, considering this time will bias the outcomes. Therefore, design time is considered to be the same for all teams (21/2 hrs.), and players are evaluated based on the time and cost measures given above.					

The above performance measurements in the game have two purposes. First, it is to make players engaged and interested in achieving the customer requirements and in passing the design constraints. Challenge is taken to be as a key criterion to engage and immerse players in the game dynamics. Garris et al. (2002) asserted that whenever a serious game is designed, game characteristics such as measuring performances and penalization motivate players. A game needs to be designed so that players are stimulated to repeat the game process, and during this iteration cycle players are engaged in the game to acquire the target pieces of knowledge and skills (Pivec and Dziabenko 2004). The second advantage of having performance measurement in the game is to compare the first and the second stages of the game.

However, in this thesis, the performance improvements of SBCE compared with PBCE are not directly measured from the performances of the game plays in the two stages. Since the game simulates a very simplified design problem, measuring the performance differences between the two stages are not taken to be effective to deduce practical implications. Moreover, during the game play, there are several problems occur that affect the time and cost performances of the players. For example, some players in a game session might not understand how to play the game, and need to spent additional time in understanding what he/she has to do in the game. So, comparing the performance differences between the two stages cannot reflect what the players (industrial players) have perceived about the difference between PBCE and SBCE. Therefore, another approach is used to measure the perceived performance advantages of SBCE and PBCE. That is, by asking the industrial players about their perceptions on the performance improvement potentials of SBCE if it would have been applied in their day to day design activities. The discussion on measuring such perceptions will be discussed in section 6.3.2.

### ***6.2.6 Stage-two of SBCE serious game***

The second stage will start once players completed designing their prototype in the first stage, and are given their performances. Teams will be introduced in an hour session about SBCE theory before starting the stage two. The introduction to the theory contains the principles and enablers of SBCE. Moreover, reflections on the results from the first game play will be explored. For example, the players will be asked the causes of design iterations and the associated costs/ consequences. During such reflection period, players and the game facilitator can identify the main drawbacks of PBCE and discuss on how SBCE can avoid the inherent shortcomings.

The second stage game takes a maximum of 1 and half hours. During the second stage game, players will not use the LEGO bricks. Rather, players use Microsoft Excel program already developed to facilitate this stage. The stage is divided into four steps to execute the different principles of SBCE as shown in see Figure 6.5. Below each step of the stage two of the game is described with some examples.

### 6.2.6.1 Step A: exploration of alternative subsystems solutions

The first step in the game is aimed at introducing players the principle of exploration in SBCE. Exploring ‘design space’ is the first step players will do in this step. Here, players won’t pick a point from a range of a customer requirement. However, they take the range of customer requirements as an input to the process. Thus, players will not freeze the requirement in this stage.

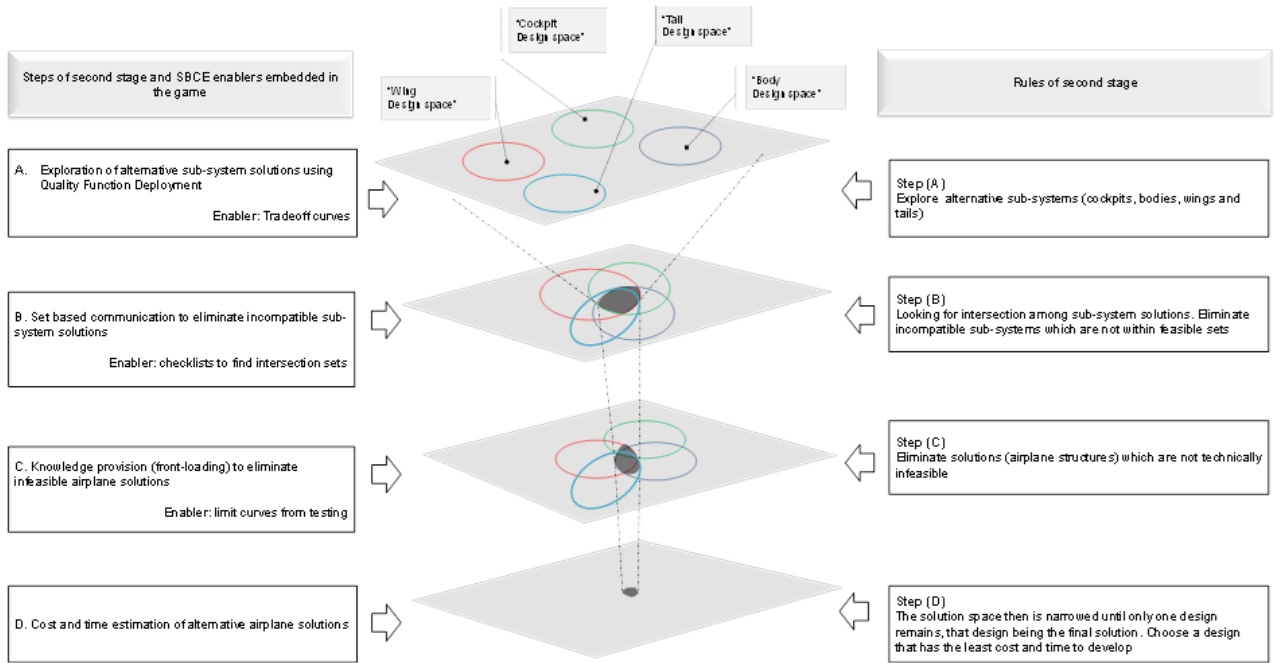


Figure 6.5: Schematic diagram of the steps in stage-two of SBCE serious game.

An SBCE enabler that is applicable in this step of the game is QFD (Quality Function Deployment). QFD is a prevalent tool used to translate imprecise customer requirements to design parameters) (Akao 1990/a and 1990/b). In SBCE game, QFD is used to generate tradeoff curves shown in Figure 6.6. For example, suppose a player who represents the body department has to explore alternative body dimensions. To explore alternative body dimensions, the customer requirement that is strictly related is number of passengers ( $N_p$ ). Then, the player will use the tradeoff curve provided to him/her (see the upper –left of Figure 6.6). Further, suppose the player belongs to group one (where  $N_p = (91, 100)$ , see Table 6.3). For this range of requirement, the player will explore alternative lengths and widths of body to define possible body modules or sizes. For this group the possible body dimensions can be drawn from the tradeoff curve of body department. Similarly for ( $w_b = 3$ ) the possible body dimensions are ( $l_b = 16$  and 18). However there is no feasible length of body that can satisfy the required range of  $N_p$  if ( $w_b = 4$ ) (see the lower – left of Figure 6.6).

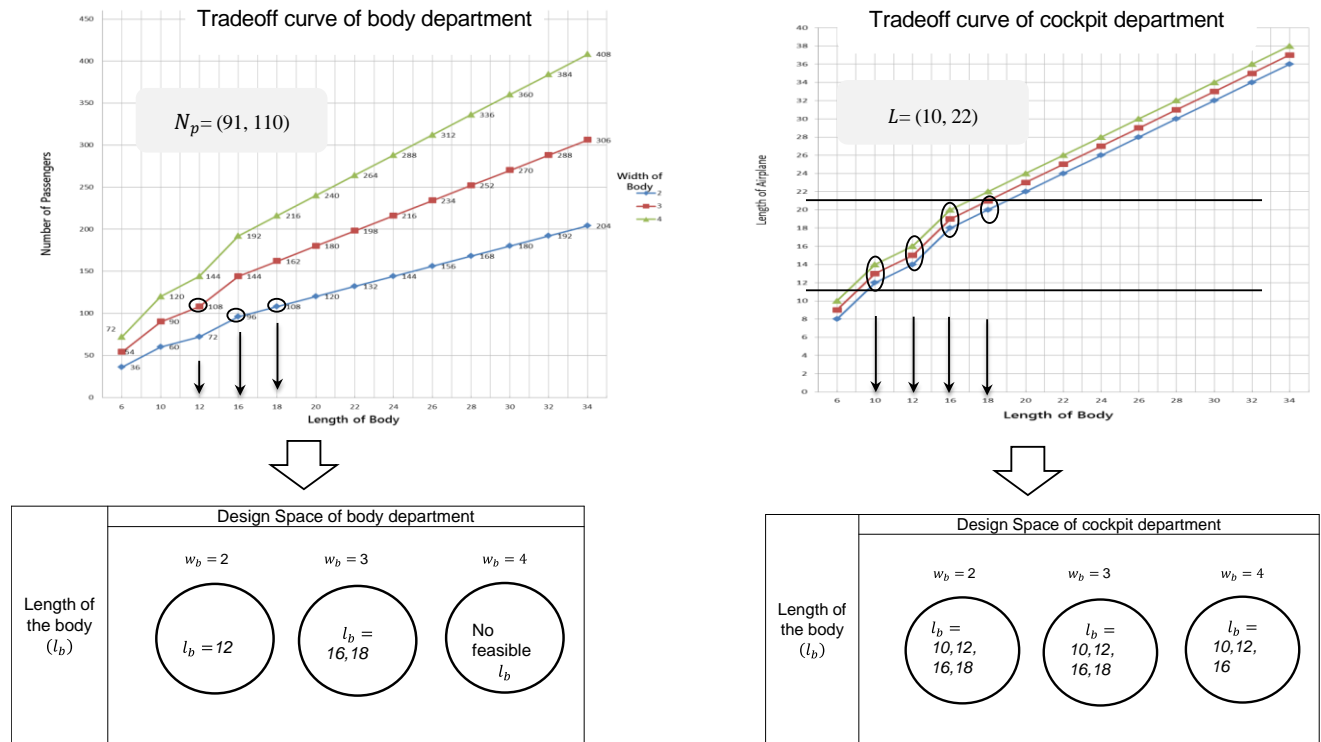


Figure 6.6: Examples of trade-offs and checklists used in the game for mapping the design space for body dimensions (example from group 1).

Similarly, a player representing cockpit department needs to define possible body dimensions from its own perspective. Although cockpit departments is concerned with defining length of the cockpit<sup>16</sup> ( $l_c$ ), it is related to with the length of the airplane ( $L$ ) and length of the body ( $l_b$ ); i.e. ( $l_c = L - l_b$ ). Using the tradeoff curve provided to the cockpit department (see the upper – right of Figure 6.6), possible dimensions of body lengths can be generated. Cockpit department therefore can define possible body modules that are acceptable from its perspective. Referring the example of group 1 where  $L = (10, 22)$  (see Table 6.3), for all widths of bodies ( $w_b = 2, 3$  and  $4$ ) the possible body lengths are ( $l_b = 10, 12, 16$  and  $18$ ), ( $l_b = 10, 12, 16$  and  $18$ ) and ( $l_b = 10, 12$  and  $16$ ) (see the lower – right of Figure 6.6 below).

There are other customer requirements and sub-systems to define. Therefore, in the game, every department is provided with the necessary tradeoff curves that are necessary to map the possible alternatives of each sub-systems (body, wing, tail and cockpit) (refer to appendices B1 and B2 to see all the tradeoff curves and checklists for cockpit, body, wing and tail).

<sup>16</sup> The length of the cockpit ( $l_c$ ) is assumed to be the same as width of the body ( $w_b$ ) as presented in Table 6.4.

### 6.2.6.2 Step B: elimination of incompatible subsystems solutions

In this step, departments will eliminate incompatible subsystem solutions which are not workable. For the example shown in the Figure 6.6, subsystem departments explore body solutions from their own perspectives. However, there are body modules which are not compatible. For example, for body department a body module with  $(w_b, l_b) = (2, 10)$  defined by cockpit department is not sufficient to satisfy any possible number of passengers (91, 100) requested. A body size with  $(w_b, l_b) = (2, 10)$  can hold only 60 passengers<sup>17</sup>. The compatible body modules are for group 1 is shown in Figure 6.7.

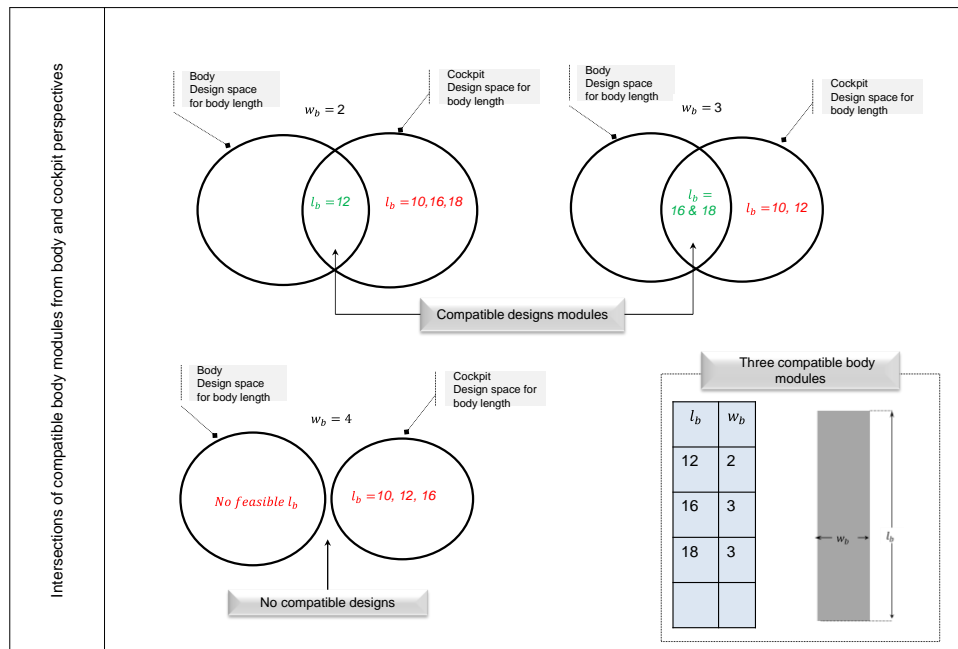


Figure 6.7: Example of defining compatible body modules form group 1.

In principles, this step is related to communicating in sets or set based communication. When the design space is large and sub-system departments have to look for intersections, then there is the need for an effective mechanism that facilitates this process in SBCE. Otherwise, the SBCE implementation faces inefficiency. In the game, the possible combinations of subsystems are few (maximum 80), so player can handle to map the compatible designs. However, in practice the combinations could be very large. For example, in US NAVY SSC program, the numbers of combinations were in a scale of  $10^{45}$  (Frye 2010). If the sets combination are very large, computer based tools can be used to define the interfaces between subsystems and eliminate incompatible solutions (Frey 2010).

<sup>17</sup> The carrying capacity can be determined as: Area \* carrying capacity of an single point which is considered as 3 (refer to Table 6.2).



### 6.2.6.3 Step C: elimination of infeasible system solutions

The third step is to utilize the limit curves to eliminate technically infeasible alternative airplane structures. From the previous step, players eliminate incompatible sub-systems, but here they will be given technical limit curves to eliminate full airplane structures. The limit curves are taken from the testing constraints listed in Table 6.4. An example of limit curve used to evaluate airplane solutions is presented in Figure 6.8. Players will eliminate those which are outside the feasible region. There are other limit-curves provide to players taking all the design constraints listed in Table 6.4. Thus, players will pick those solutions which are feasible for all the constraints.

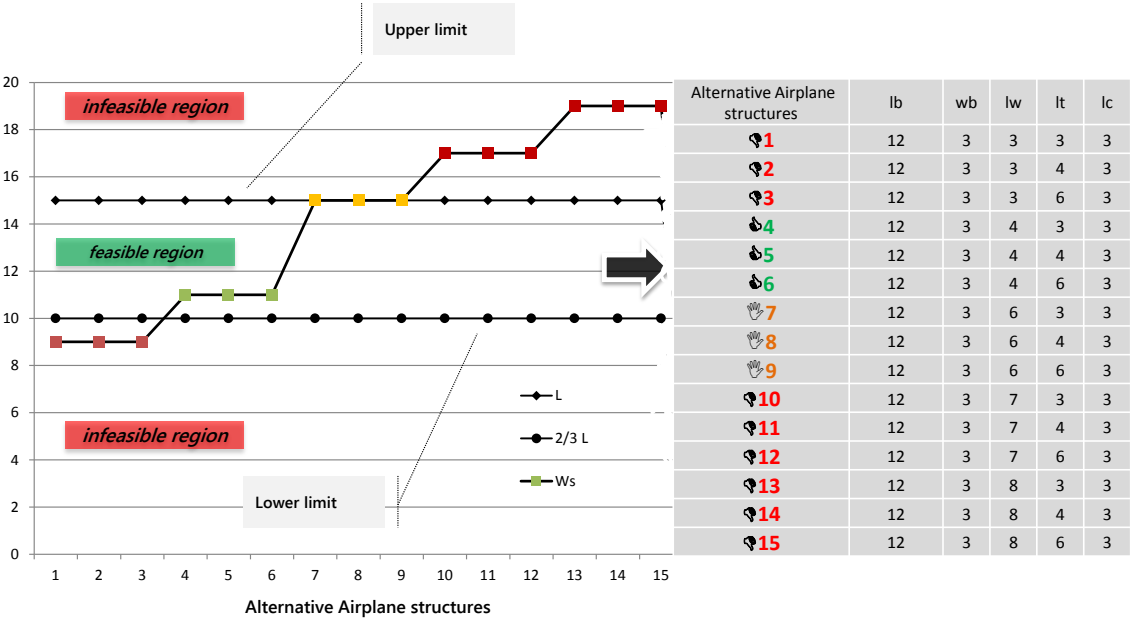


Figure 6.8: Example of a limit curve to evaluate alternative airplane structures (limit curve constructed from the testing constraint  $\frac{2}{3}L < ws < L$ ).<sup>18</sup>

As discussed in section 3.1.4 of this thesis, limit curve is one of the most key enabler for convergence process. Ward et al. (2007) underscore that Toyota uses limit and tradeoff curves extensively in SBCE process. Limit curves in practice can be generated through testing a solution or set of solutions at different working conditions. Generating limit curves have several advantages apart from evaluating sets. It is a knowledge provision mechanism, where knowledge captured in visual and generalized forms can be effectively reused in future projects. Once alternative designs are tested at different conditions in a project,

<sup>18</sup> ☞ Eliminate alternatives: 1, 2, 3, 10, 11, 12, 13, 14, and 15; ☞ Pursue alternatives 4, 5, and 6; ☞ Alternatives 7, 8, and 9 are on the upper limit of the constraint, players can pursue these alternatives but in reality these alternatives might be risky airplane structures.

another project might need such test results to understand technical feasibilities. As a consequence, time for testing will be reduced, and the risk of failures can also be minimized. It also facilitates learning, designers can learn about the technical performances of alternative solutions by testing several of them at range of working conditions. Therefore, in SBCE game, the limit curves are embedded to let designers and managers understand the potentials of limit curves in capturing and providing technical knowledge, and facilitate elimination process in SBCE (refer to appendix B3 to see all the limit-curves used in game).

#### 6.2.6.4 Step D: selection of an optimal system

The final step is to evaluate feasible alternative airplane structures and choose the best one taking objectives criteria such as cost and time of development introduced in Table 6.5 and Table 6.6. Referring to the tables, in this step  $ci$  and  $it$  are zero, since all the causes of failures are anticipated in step C and no design iteration is encountered. Similarly, since all the ranges of the customer requirements are deployed in exploration phase (step A), the cost of penalty ( $cp$ ) is zero. Although this assumption takes an ideal scenario, in practice SBCE helps to drastically reduce unnecessary late design reworks and missing customer targets (Raudberget 2010).

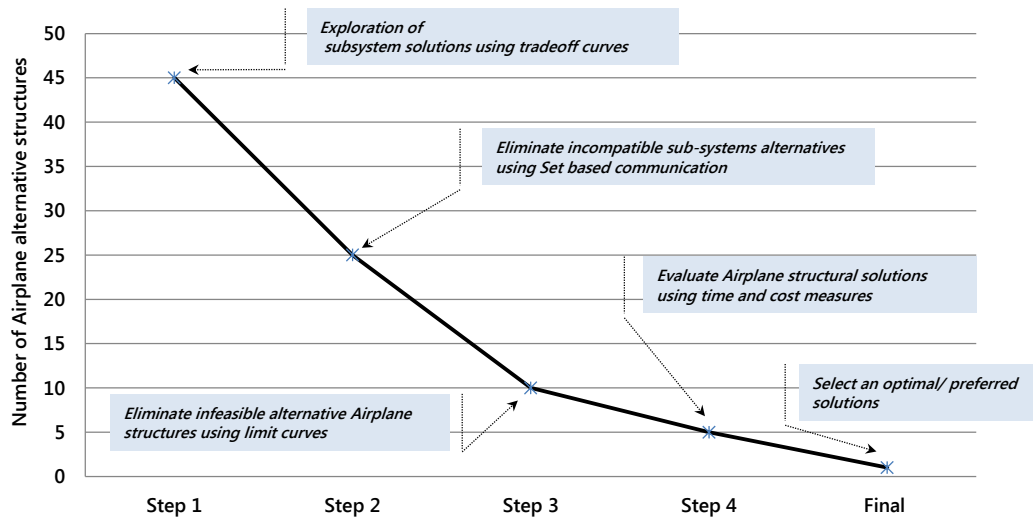


Figure 6.9: Set reduction process in stage two of SBCE game – an example from group 1.

In summary, the players in stage two explore alternative sub-systems using tradeoffs (step A), then evaluate the sets compatibility using checklists provided (step B), then progressively eliminate infeasible full airplane structural solutions (step C) using the limit curves provided from testing constraints, and finally evaluate feasible solutions based on cost and time of development to select a preferred solution (step D). See Figure 6.9 for an example of set reduction in stage two of the game from players in group 1. As it can be seen, in SBCE process there is no selection before compatibilities and feasibilities are proven. This is what the game finally tries to introduce to practitioners.

### 6.2.6.5 *Measuring the learning outcomes in SBCE serious game*

Once players finished playing the SBCE game, it has been the aim of the research to measure how much the awareness level about SBCE has improved and how practitioners perceive SBCE in terms of its pros and cons. In order to measure the learning outcomes, the prevalent framework of Garris has been used. Garris et al. (2002) identified three level of learning aspects in order to measure the effectiveness of a SG: *Declarative, Procedural, and Strategic learning*. They are explained briefly as follows:

- *Declarative learning*: the first of the three aspects of learning in SG is the learning of facts or increasing one's knowledge about a subject. Frequently, SGs concern a specific problem or real world situation and are developed from a certain theoretical background. In games, one of the learning objectives is to increase the domain understanding of players. In SBCE game, the understanding of the SBCE theory and its supporting enablers by players are considered as parts of the declarative learning outcomes.
- *Procedural learning*: this aspect refers to the learning of procedures, and also to the understanding of patterns of processes and behavior. In the SBCE game, procedural knowledge is related to players' ability to associate the specific elements of SBCE process and the benefits of using them to support a better decision making. This learning dimension is assumed to reflect learners' perception about the performance advantages of SBCE if applied in a real life scenario. Of course, there were performance measurements related to the game stages one and two. But, comparing PBCE and SBCE taking only the measures in the game are not taken to be informative. Because, the game represent a simplified form of reality. More interesting indicators for procedural leaning in the SBCE game is therefore the "perceived performance advantages of SBCE" such as reduction in product/ process cost, improve innovation, improve quality, facilitate effective communication, risk reduction, and improve learning.
- *Strategic learning*: the third learning aspect is that of increasing intellectual ability. Within gaming this aspect has been explained as implementing knowledge from the game in new (real-world) situations. Gaming can also contribute to developing reflective competences. Within complex systems as in PD, it is not only refers to implementing what is taught in the theory but also observing behavior and adapting to new situations. In SBCE game, several complexities have been simplified but adequate complexities are also added to keep players engaged. Since extant literature does not provide sufficient information on the practicality of applying SBCE in different context that big OEMs, investigating the strategic learning outcomes of playing the game is insightful.

## 6.3 Validation of SBCE serious game in industry

The game has been played by designers and managers of an Italian company (Carel Industries) who designs and manufactures products in HVACR (Heating, Ventilation, Air-conditioning and Refrigeration) market. In total, there were more than 60 players who played the game in the company, but only 49 responded to the questionnaire provided. Therefore, the measurement of the learning outcomes is based on 49 designers (Mechanical, Electrical, and Software designers) and managers (product and project leaders). The demographics of players are presented in Table 6.7. The game was played in 3 sessions. In each session there were around 4 or 5 teams. Three facilitators were helping players in order to let them understand the game's steps and rules.

The players are all from the same company and work together in the same physical vicinity. Although the sample size is limited to have external validity results, interesting insights can be obtained within this one company's context (Norman 2010; Carifio and Perla 2007). In particular, Norman (2010), Carifio and Perla (2007) dismissed the argument by other researches indicating that statistical results based on small samples size have methodological limitation in terms of external validity. Therefore, statistical results within the context of one company case can highlights useful and valid results, both to the practice and theory. In fact, 49 designers and managers can represent a good sample size to measure the learning outcomes of the SBCE game; given that there are about 100 designers/managers involved in the company's PD. Moreover, appropriate statistical tests are used to make inferences while measuring the learning outcomes.

Table 6.7: Demographics of SBCE game players in the company (N = 49).

Classifications	Categories	Percentage (%)
Age (years)	< 40	41
	≥ 40	59
Domain	Designers	37
	Project managers	63
Years of experience	< 12	43
	≥ 12	57
Gender	Male	84
	Female	16



To measure the learning outcomes of the players a questionnaire based on 'Likert five scale' model is prepared (Likert 1932). The scale for a question is taken from 1 to 5 (where 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree). The questions were divided into three main learning aspects; declarative (D), procedural (P) and strategic (S) based on Garris et al. (2002) framework as discussed above (refer to Appendix C1 to see the questionnaire). Since almost all players were Italian, the

questions were translated to Italian language to make sure that respondents understood the questions and feel comfortable to respond. The questions are then asked to players after finishing the game. However, before the players were distributed the questionnaire, detail discussions were made about the PBCE and SBCE and the SBCE enablers embedded in the game. The discussions on the results of measuring the learning outcomes are explained in the following subsections.

### 6.3.1 Declarative learning outcomes

As discussed before, in the second stage of the game, players were introduced about SBCE and played how it can be executed taking a simplified airplane structure as a gaming object. There are nine questions related to this learning aspect. Table 6.8 shows the questions asked and the summaries of the results obtained.

Table 6.8: Questions for measuring the declarative (D) learning outcomes and summary of response results.

Code	Questions – is playing the game help you understand:-	$\mu$	$\sigma$
D1	how SBCE works along with its enabling tools	3.73	0.95
D2	how to explore alternative solutions using the tools played in the game	3.97	0.69
D3	to communicate about set with my team than one solution	4.06	0.72
D4	the challenge of designing a product that fully satisfy customer requirements	3.81	0.73
D5	the challenge of designing a product that fully satisfy testing requirements	3.75	0.75
D6	understand the problem of communication within a PD team	3.86	0.87
D7	to effectively understand the usage of limit-curves	3.78	0.71
D8	how to communicate with my teams about sets of solutions	3.83	0.56
D9	the importance of capturing design knowledge in a in the form of trade-off and limit curves	4.1	0.77

Moreover, Figure 6.10 shows the descriptive statistics of the declarative learning results. From the results, it is clear that, the game has been effective in transferring the theory of SBCE principle and enablers. It helped designers and managers to understand how SBCE works (D1), how to explore alternative solutions (D2) and communicate in sets rather than single solution (D3) with mean responses of 3.73, 3.97 and 4.06 respectively. Furthermore, the game has been effective in transferring the concept of knowledge capturing in the form of tradeoff and limit curves (D9) with mean response of 4.1. From the discussions we had with players, SBCE process has been a unique approach compared with the one they follow in PD.

One of the mixed responses the game obtained is for D5, where player asked if the games help them to understand the challenge of designing a product that fully satisfy the testing requirements (D5). For this question, about 35% of the respondents were either neutral or disagree on the question. Perhaps, the question

is overly stated by implying “fully”. For practitioners, the challenge is tremendous in real life than the game. The game is the simplification of reality, where few constraints are considered.

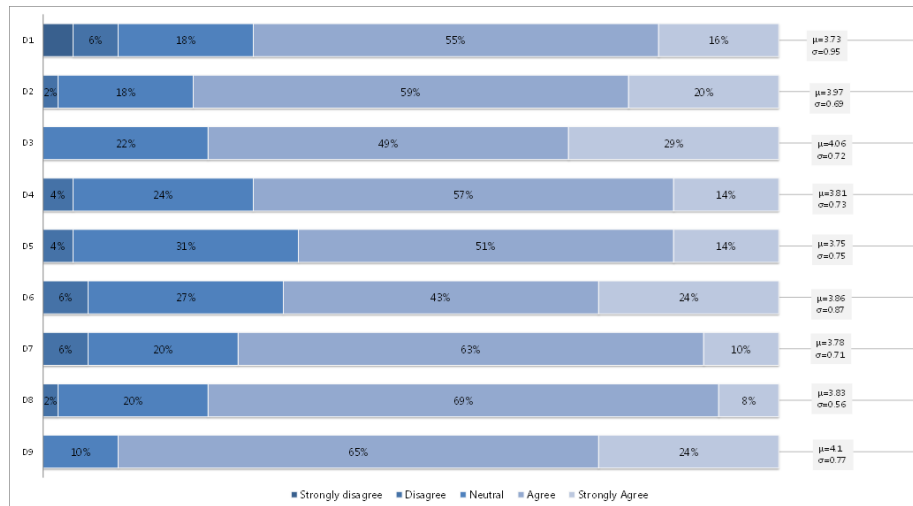


Figure 6.10: Descriptive statistics of declarative learning outcomes (N = 49, μ = mean and σ = std. dev.).

### 6.3.1.1 Set based communication and its practicality

Another question that might need attention is D6, where about 33% of the respondents were either neutral or disagree on the question. The best explanation for this response is related to designers’ experiences about communication during design process. Communication in the game was taken as set based communication not communication in the form of meetings or its other traditional common interpretations. Set based communication is necessary when sub-system designers explore alternative solutions and need to evaluate sets to check for subsystems compatibilities.

During the discussion with players, three observations have been made about the result on question D6. First, the product the company designs is for HVACR market. Product types in this market are not like automotive where set based communication is pronounced as key principle for SBCE. In Toyota, for example, there are large numbers of subsystems that designers should explore and need to check compatibilities of sets during new vehicle launch (Liker, et al. 1996). For HVACR products, subsystems are not as tightly coupled as automotive that might demand set based communication either with internal subsystem teams or suppliers. Moreover, the major types innovation on new products made in the case company is incremental. This fact reduces the broadness of the sets to consider, as a consequence simplifies communication among functional teams.

The second reason is related to the case company being small. During new development projects, often the suppliers of the case company requires very detail specifications to start building a prototype for a new

project. There are little negotiation power to force suppliers to explore alternative components and present performance curves. This limit the level of set based type communication between the company and its suppliers. Therefore, it becomes difficult to leverage on suppliers capabilities as big OEMs could have. The success of SBCE in Toyota partly can be attributed to its bargaining power to leverage suppliers' capabilities to facilitate SBCE process. Before bidding, suppliers of Toyota are required to explore several alternative prototypes, test them in different working conditions and bring performance results in the form of trade-off curves (Ward, et al. 1995; Sobek and Ward 1996; Sobek, et al. 1999; Ward, et al. 2007). Toyota thus offsets the extensive portions of SBCE process to partners, and pulls knowledge to support its internal processes. Nonetheless, such kind of opportunities might not be available for many industries (e.g. small or medium sized companies).

The third reason for the result of question D6 is related team size in a new project. Most projects are done with few people and sometime only one person owns a full project. Thus, communication in sets might not be a critical because there are close collaboration between few and collocated designers and managers. Moreover, if one designer is responsible to design different subsystems, communication in sets becomes simple. However, the company is going global; it is opening design and development offices in different countries such as China, Brazil and USA. If subsystems are designed across different non-collocated or multiple designers, then set based communication becomes an important enabler for SBCE.

### **6.3.1.2 Designers vs. Managers in SBCE**

Another observation that can be made from Figure 6.10 is question D1, where players were asked about their level of understanding about SBCE process after the game. Although most players (71%) either agree or strongly agree that the game increases their understanding, there is a higher level of variation between players ( $\sigma = 0.95$ ). This might have arisen from the difference in understanding between designers and managers.

In order to test if there are significant differences between groups of SBCE game players, a non-parametric test is used. Since the data are ordinal (Likert) scales, the most appropriate test is based on group median differences, and Mann-Whitney U test is the most prevalent and recommended one (Siegel 1957; Newson 2001). Moreover, STATA 2010 statistical package is used for data analysis.

As shown in Table 6.9, interesting difference can be observed. Designers and managers are different in understanding the limit curves (D7) and communication in sets (D3) with significant levels of  $p \leq 0.01$  and  $p \leq 0.10$  respectively. Looking at the rank sums in Table 6.9, managers give much higher ranking for both questions than technical designers (900.5 for D7 and 851.5 for D3). This have been observed during the game too, managers have pre-information about SBCE from reading lean product development books,

attending seminars and conferences. However, most technical designers are new to SBCE. If the differences arise because managers are pre-aware about SBCE, that will cause less problem during a real implementation phase. However, if the differences arise from “cultural” issues, that is, if designers don’t appreciate new way of working than the norm, then, it will be difficult for managers (product and project leaders) to disseminate the concept of SBCE and obtain a wider acceptance throughout the company.

### 6.3.1.3 *People experience and SBCE*

The other difference which is worth mentioning in Table 6.9 is between highly and less experienced players. There is a significant difference between highly and less experience players on question D5 with significance level of  $p \leq 0.05$ . The result shows that, less experienced players recognize the difficulties of satisfying testing requirements (or, other downstream constrains) than highly experienced players (D5). Looking at the rank sum in Table 6.9 for D5, less experienced designers rank the question higher (614) than highly experienced designers (611). From the feedback obtained, less experienced designers in the company indicated that there are several failure causes which are difficult for them to anticipate in early phase of new design projects than the experienced ones. Thus, test results generating in limit curves are identified as paramount generalize knowledge and facilitate effective risk mitigations in future projects.

On the other hand, there is a significant difference between highly and less experience players on question D6 with significance level of  $p \leq 0.10$ . The result shows that highly experienced designers recognize the challenge of communication in SBCE process (D6). Looking at the rank sum in Table 6.9 for D6, highly experienced designers rank the question higher (777.5) than less experienced designers (447.5). In practice, experienced designers are at the center of communication. In particular, in smaller or medium sized companies, where there are few highly experienced designers, the less experienced designers have to communicate frequently with more experienced colleagues to get information and data. Thus, experienced designers become overwhelmed by frequent coaching and mentoring. For this reason, player with higher experience appreciate to have tools to effective capture and document knowledge, so that technical information is well captured and transferred to novices.

Table 6.9: The Mann-Whitney U tests for declarative learning outcomes (rejected hypotheses are reported).

Null Hypothesis	Measure of declarative learning measures	Rank sum (1/2)	U-Test: p-values
Median (1) = Median (2)			
Male = Female	D9: The game gives me insights about the importance of capturing design knowledge in the form of tradeoff and limit curves	965/260 <sup>(*)</sup>	0.0534



n (1) = 41 n (2) = 8	D4: The game help you to understand the challenge of designing a product that fully satisfy customer requirements	962/263 <sup>(§)</sup>	0.0561
	D1: The game let you understand how SBCE works along with its enabling tools	966.5/258.5 <sup>(§)</sup>	0.081
Designers = Managers n (1) = 18 n (2) = 31	D7: The game help me to effectively understand the usage of limit-curves	324.5/900.5 <sup>(**)</sup>	0.0024
	D3: The game help me to communicate about set with my team than one solution	373.5/851.5 <sup>(§)</sup>	0.0850
Years of experience ≥ 12 = Years of experience <12 n (1) = 28 n (2) = 21	D5: The game help you to understand the challenge of designing a product that fully satisfy testing requirements	611/614 <sup>(*)</sup>	0.0492
	D6: The game help you to clearly understand the problem of communication within a product development team	777.5/447.5 <sup>(§)</sup>	0.0966
Key: <sup>(§)</sup> $p \leq 0.10$ , <sup>(*)</sup> $p \leq 0.05$ , <sup>(**)</sup> $p \leq 0.01$ , $n =$ sample size, Gender: Male (1) and Female (2), Domain: Designers (1) and Managers (2), Years of experience: Above average (1) and Below Average (2).			

### 6.3.2 Procedural learning outcomes

Procedural aspects of the learning are used in the game to measure the “perceived” performance advantages of SBCE compared to PBCE. The term “perceived” is chosen because the game cannot reflect the real performance gains of SBCE. Moreover, as Hoppmann (2009) and Ward et al. (2007) indicate, the successful implementation of SBCE process in a company might take considerable time to be fully exploited. Since SBCE demands changes in several practice areas, significant performance improvements might not guaranteed in short terms. Therefore, a more sensible approach to measure the performance leverage in implementing SBCE is by asking practitioners how they “perceive” its advantages in real case scenarios. Using SBCE game actually helped quite significantly to accurately ask practitioners. Since the players played both scenarios (PBCE and SBCE in the first and second stages of the game) they have a good understanding on the questions asked. Moreover, the theoretical implications of SBCE on performances were presented to them before starting and after finishing the second stage of the game. Therefore, the reflections on the perceived performance benefits of SBCE by practitioners can be a valuable input to the existing body of knowledge.

The seven performances related questions asked to players and the related explanations are given as follows:

- *Reduction of product and process costs (P1)*: product cost can be minimized in SBCE effort. It can be achieved either through finding less costly alternatives in a design space or by adding the right product features that customers want (i.e. avoiding over-design). Process cost can be reduced in SBCE effort by reducing late design changes, which might cause rework costs and missing market opportunities.
- *Reduction of development time (P2)*: development time can be reduced either by reusing knowledge from the previous projects, and/ or by avoiding extra time caused by late changes once infeasibilities from testing department are revealed.
- *Improve innovation potential (P3)*: better innovation can be gained in SBCE implementation directly and indirectly. A thorough exploration and mapping of design spaces might give some design alternatives that never been exposed before. There is also indirect way to obtain product innovation, if designers waste less time in doing what others already did before them; it leaves more time to work on new ideas. Thus, testing several solutions and provisioning them into limit and tradeoff curves can help in avoiding knowledge waste and foster (indirectly) innovation.
- *Better communication with teams (P4)*: this improvement can be achieved with set based communication discussed earlier and with SBCE's enablers for knowledge provision. Set based communication help designers and managers to effectively communicate about the performances of sets (of solutions). Moreover, if the communication is based on data and proven knowledge, it is much more beneficial for the other performances such as time, cost, and risk and so on.
- *Avoid design risks (P5)*: design risk is defined in the game as the probability that an airplane structure fails during testing phase. Players understood this fact, and obviously frontloading information about testing constraints in the beginning of stage two reduces the risks of failures. Moreover, the consideration of alternative solutions brings more chances to pass failures during testing or other constraints that might arise during development process.
- *Improve product quality (P7)*: quality has several definitions, but Crosby's (1979) definition as "conformity to requirements" might best fit into SBCE game context. In the game, there are both external customer and internal customer (testing department) that players consider to satisfy. Customer requirements were fixed early in stage one of the game, but in the second stage, possible requirements of customers was considered as range of values. Thus, it helps players to consider all the possible design alternatives that the customer might look for within a given range of customer requirement. Therefore, considering the customers requirement as a range brings more chance to satisfy the customer requirements. Similarly, testing department (as internal customer) will get the design right as early as possible. As a result, higher quality levels can be achieved at the right time for customers.

- *Facilitate learning (P7)*: learning is the basic essence of SBCE. Its basic objective, among other performance improvements mentioned above, is to make a development organization to be a learning one. Learning from failures, learning from others and learning from extensive testing. Moreover, it is not only learning that make SBCE a sensible approach to PD, but also learning what has been learnt from the past or present.

### 6.3.2.1 *Perceived performance benefits of SBCE*

Players were asked if SBCE can have positive impacts on the above performance measures. Similar format has been used (as declarative learning outcomes) to construct the questions and assesses the procedural learning outcomes (Likert five scale model). Figure 6.11 shows the summary of the descriptive statistics of the responses. From the chart, it can be seen that avoiding design risks is the most agreed advantage of SBCE as perceived by industrial players (88% agree or strongly agree, with mean response of 4.1). This is clearly obvious since in the first stage of the game (PBCE), players failed to pass the testing conditions at least one or two times. However, in the second stage since the game provides enablers of SBCE to explore all available solutions and frontload the design process with knowledge (testing constraints), there were less risks of failures. It is true in practice as well. If designers are able to frontload knowledge from downstream functions, many of risks could have been avoided. Similarly, the other advantages of SBCE as perceived by industrial players are reduction of product/ process costs (73 % agree or strongly agree, with mean response of 3.8) and facilitating learning (71 % agree or strongly agree, with mean response of 3.8).

### 6.3.2.2 *Innovation and SBCE*

Except improving innovation potential and communication, SBCE is perceived as a process that can improve performances if implemented in their company. The discussion related to the ineffectiveness of set based communication in this particular company is already elaborated in section 6.3.1.1 above. Here let's observe the improvement of innovation potential of SBCE.

Fifty percent (half of the players) are neutral or disagree about the SBCE's potential to foster innovation. This is a key lesson for SBCE body of knowledge. Industrial practitioners think that innovation is finding new or unexpected solutions. So, does adopting SBCE enable designers to find out new solutions? The answer primarily depends on how the exploration principle of SBCE is executed. As discussed in chapter 4 (section 4.6) there are several tools and methods that can be used to exploration alternative concepts. If, for example, brainstorming (Osborn 1957) is used to generate conceptual design solutions, the level of innovation is strongly depends on the abilities of designers who are involved in the idea generation process. But, brainstorming and similar methods are not structured ways of generating ideas and capturing the idea

generation process (e.g. why some ideas are rejected and some are accepted are not well captured). In order to structure such a process and decouple the dependency on the designers' capabilities, Toyota uses tradeoff curves (Ward, et al. 1995). In tradeoffs analyses between alternative solutions, one might capture the knowledge about the performances of the alternatives and facilitate effective discussions among designers. That's why tradeoffs curves are used in the second stage of the SBCE game. However, using tradeoffs restricts the level of innovation (Altshuller 1984, 1994, 1999). Altshuller is one opponent of using tradeoffs in product design. He argued that, accepting tradeoffs will not lead to innovative or inventive solutions. Rather, using tradeoff analyses limit innovation because designers explore solution accepting compromise between performances. For example, if a designer is challenged to choose among material types aiming at reducing weight and maximize strength, using tradeoff analyses he/ she might come up with a material that have an average weight and an average strength (compromising the two requirements). However, Altshuller's theory which is called TRIZ (Theory of Inventive Problem Solving) has different approach to find solutions (Altshuller 1984, 1994, 1999). In TRIZ, tradeoffs are not accepted, rather they are eliminated. In the above material choice example, the TRIZ approach is to lead the designer to think out of the box and come up with a material which has the less weight and at the same time high strength. TRIZ provides several methodologies to facilitate and structure to find such inventive solutions (e.g. the 40 inventive principles, principles of separation and algorithms for inventive problem solving).

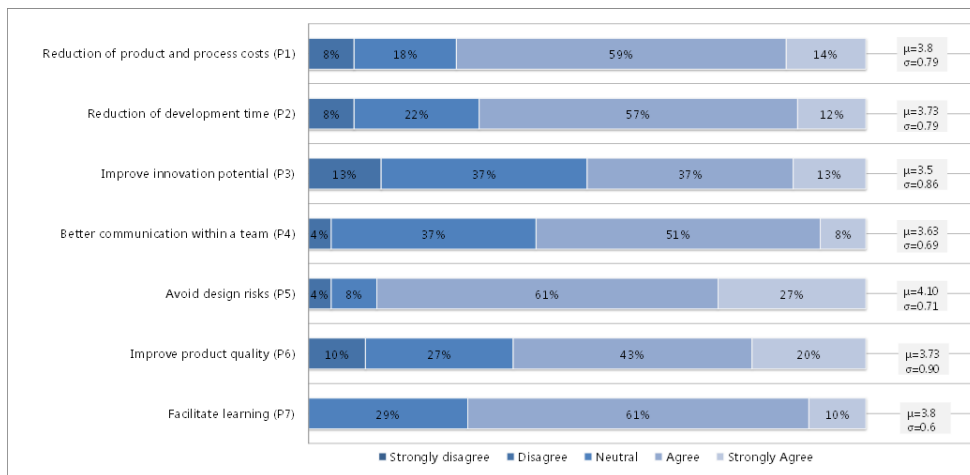


Figure 6.11: Descriptive statistics of procedural learning outcomes (N = 49, μ = mean and σ = std. dev.).

Therefore, yes it is true that SBCE might not lead to innovative solutions. But, if tradeoff analyses are used to explore design solutions and map the design space, designers normally windup with known solutions (and accept design compromises). But, if methodologies such as TRIZ are systematically integrated, SBCE can be a process to support innovation. Moreover, it is difficult to generate and understand tradeoffs in a product

system, and even impossible in some cases to model. Therefore, appropriate strategies should be applied at the beginning of SBCE process to explore innovative solutions.

### 6.3.2.3 Perceptions of SBCE benefits: Designers vs. Managers

Table 6.10 shows the inferential analyses. The table also shows the reject hypotheses on perceived performance advantages in different groups. Once again, there are statistically significant differences ( $p \leq 0.01$ ) on the medians between managers and designers in perceiving the advantages of SBCE on questions P5 and P7. For both performances managers give higher ranks (883 for P5 and 896.5 for P7) than designers (342 for P5 and 328.5 for P7). The most appealing interpretation could be that, managers might have pre-inclinations with the notion that SBCE can improve performances and are eager to adopt SBCE as one lean initiative. However, managers should give considerable attention to convince technical designers on the real benefits of SBCE to gain wider acceptance before implementation.

Table 6.10: The Mann-Whitney U tests for procedural learning outcomes (only rejected hypotheses are reported).

Null Hypothesis Median (1) = Median (2)	Procedural learning measures	Rank sum (1/2)	U-Test: p-values
Age $\geq$ 40 = Age $<$ 40 n (1) = 20 n (2) = 29	P1: Reduction of product and process cost, by reducing rework and penalty cost	574/ 651 <sup>(#)</sup>	0.089
Designers = Managers n (1) = 18 n (2) = 31	P5: Avoiding design risks	342/ 883 <sup>(**)</sup>	0.0098
	P7: Improve product quality	328.5/ 896.5 <sup>(**)</sup>	0.0035
Key: <sup>(#)</sup> $p \leq 0.10$ , <sup>(*)</sup> $p \leq 0.05$ , <sup>(**)</sup> $p \leq 0.01$ , $n$ = sample size, Age: Above average (1) and Below Average (2), Domain: Designers (1) and Managers (2)			

### 6.3.3 Strategic learning outcomes

The final learning aspect that is assessed in the SBCE game is the strategic learning outcomes. It is primarily concerned with the adoption of what has been learnt from the game into real-life design scenarios. Industrial players were asked about ten questions that might reflect if they can adopt some of the principles and enablers of SBCE to their real design activities. Table 6.11 shows the list of questions and summaries of the descriptive statistics results. The descriptive statistics for the responses are also shown in Figure 6.12.

In general, the game has been perceived as useful to practitioners. More than 70% of the players were responding for questions S1, S2, S4 and S7 as either agree or strongly agree. These responses reflect that, the tradeoff curves, limit curves and the checklists have been taken as useful hints on how to make the design and development process better.

### 6.3.3.1 Problem solving and SBCE

The response to S5 is mixed, around 40 % of the respondents were not sure if SBCE can improve their problem solving abilities. This question might not be well understood by players or the game was not effective in reflecting what problem solving means in the game context. The question were addressing to ask if problems that might results in delays and additional costs (such as product failure during testing) could have been solved by applying some of the enablers embedded in the game (such as limit curves, checklists or tradeoff curves).

Table 6.11: Questions for measuring the strategic (S) learning outcomes and summary of response results.

Code	Questions – is playing the game:-	$\mu$	$\sigma$
S1	help you on how to use trade-off and limit curves in design practice?	3.65	0.69
S2	help you on how to develop communication tools for evaluating sets in practice?	3.78	0.51
S3	help you on how to better communicate in practice?	3.61	0.64
S4	worthwhile for your design practice?	3.98	0.72
S5	help you on how to improve your problem solving skills in practice?	3.53	0.68
S6	help you to believe that SBCE is better approach than normally practiced?	3.71	0.84
S7	will help you to develop set of solutions than one?	4.08	0.70
Code	Questions	$\mu$	$\sigma$
S8	It is possible to develop trade-off/limit curves in our new projects and it is not easy?	3.55	0.89
S9	It is possible to develop trade-off/limit curves in our new projects and it is easy?	2.4	0.79
S10 <sup>19</sup>	It is not possible at all to develop trade-off/limit curves in practice?	2.27	0.86

As understood from the feedback given by players, designers and managers associate “problem solving” in a different way than portrayed or asked in the game. Most problems that the designers face during development processes are project delays. There are some initiatives for example visual planning schemes to address problems that might avoid delays. That means, problem solving could mean different for different

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<sup>19</sup> Reverse ordering for the negative question S10 (Norman 2010).

people. For most designers, problems might be associated with “over-burden”, for example. Moreover, projects are delayed because designers are over-burdened with many other projects.

SBCE might not directly be related to overburden at the first site. However, it’s what Ward et al. (2007) expressed it as the opposite of one piece flow. Flow in product development can be achieved by allocating the right amount of work-load to designers at different stages of the process. If designers are given project plans which cannot be achieved within their available time, then flow cannot be achieved. That is why integration events are taken as one of SBCE’s enablers. Integration events should substitute stage-gate controls during SBCE implementation (Ward, et al. 2007; Oostewal 2010). Gate controls as practiced in most companies are “evils” (Oostewal 2010, pp. 148). Gates are planned based on wrong assumptions about the nature of product design and development process. PD is unpredictable and cannot be controlled by gates that dictate deadlines which are not achievable. Once plans are scheduled, designers become overloaded and problems will be found out late the process causing delays and cost overruns. Although in SBCE game integration events are not strictly considered, it is one of the enablers of SBCE (refer chapter 4, section 4.4). Moreover, enabling tools that are introduced in stage-two of the SBCE game are used at integration events to evaluate sets, facilitate negotiation between teams, and make effective planning.

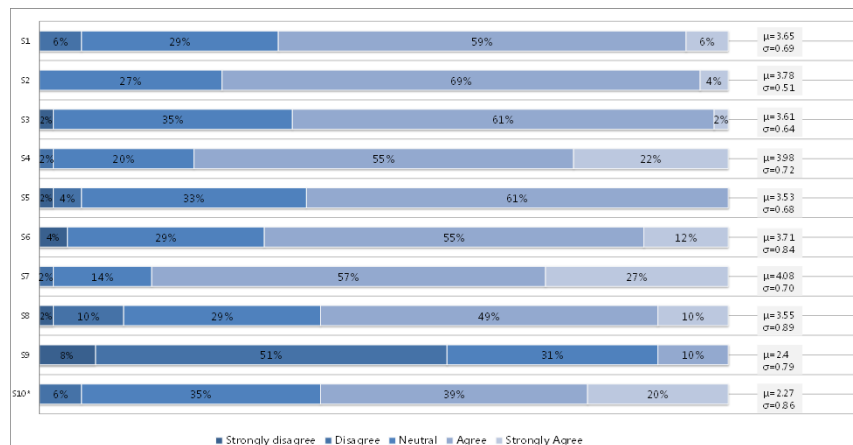


Figure 6.12: Descriptive statistics of strategic learning outcomes (N = 49,  $\mu$  = mean and  $\sigma$  = std. dev.).

### 6.3.3.2 Challenge in generating tradeoff and limit curves

Another important note that can be taken from Figure 6.12 is the responses to question S9 ( $\mu = 2.4$ ), which asks if developing tools such as tradeoff/limit curves are easy for their products. However, most of the industrial players recognize that building such knowledge instruments is not an easy job. This shows how SBCE demands time to be effective before seeing any performance improvements after implementation. In particular, small and medium sized companies have limitations in resources to invest on simulation and

testing tools to generate tradeoffs and limit curves. Moreover, generating alternative designs and building prototypes in parallel will be costly for these companies to capture and analyze governing performances data about sets. Thus, as many lean initiatives, SBCE should be taken as a process and as a journey where knowledge is systematically captured as a long term strategy.

### **6.3.3.3 *Interests to adopt SBCE: Designers vs. Managers***

Inferential statistics also done to see if there are differences among players groups on their tendencies to apply what have been learnt in the SBCE game. As shown in Table 6.12, there are statistically significant differences on the medians of the responses between managers and designers on questions S4 and S7. Considering S4, management is willing to proceed with the adoption of SBCE process in the company (rank sum = 848). Compared to that of the designers' ranking for the question (rank sum = 377), there is a significant difference between the two (with significance level of  $p \leq 0.10$ ). In fact, the management is deploying a pilot case on the company to test SBCE in a product. This is a remarkable initiative; however, care should be taken underlying the fact that SBCE is a journey that demands the involvement of designers and technicians alike for its successful implementation.

### **6.3.3.4 *Competence development in SBCE***

Looking at Table 6.12, there are statistically significant differences between those players who have more than average years of experience and the others on questions S5 and S9. These differences have very important implications to underline.

Recalling the discussion on chapter 4, section 4.3, one of the key enablers for SBCE is people competence. The roles of experienced engineers and designers are paramount for successful implementation of SBCE. For example, one of the roles of the Chief engineers (CEs) in Toyota are mentoring and transferring knowledge to novice (less experienced) about customers, market, technical competences (Morgan and Liker 2006). Similar implications have been observed from the game measurement too. For example, the rank sum from experienced designers (787) is higher than the less experienced designers (435) on question S9, and the two groups are statistically different for significant level of  $p \leq 0.10$ . The result implies that, players with highly practical experience know how to identify and capture technical data (e.g. test data) from downstream processes compared to their colleagues with less years of experience. Therefore, it is important to underscore the issue of coaching and mentoring. It is recommended for highly experienced designers to formally and informally run mentoring activities during SBCE process.



Table 6.12: The Mann-Whitney U tests for strategic learning outcomes (rejected hypotheses are reported).

Null Hypothesis Median (1) = Median (2)	Strategic learning measures	Rank sum (1/2)	U-Test: p-values
Designers = Managers  n (1) = 18  n (2) = 31	S4: Playing the SBCE game is worthwhile to your product development process	377/848 <sup>(§)</sup>	0.0931
	S7: The game help me to design sets of solutions rather than one solution	355.5/869.5 <sup>(*)</sup>	0.0277
Years of experience ≥12 = Years of experience <12  n (1) = 28  n (2) = 21	S5: Playing SBCE game will improve your problem solving ability in new product design	624.5/600.5 <sup>(*)</sup>	0.0754
	S9: It is possible to develop some limit-curves (as shown in the game) for a product I a am designing and it is easy	787/435 <sup>(§)</sup>	0.0547
Key: <sup>(§)</sup> $p \leq 0.10$ <sup>(*)</sup> $p \leq 0.05$ <sup>(**)</sup> $p \leq 0.01$ , $n$ = sample size, Gender: Age: Above average (1) and Below Average (2), Domain: Designers (1) and Managers (2), Years of experience: Above average (1) and Below Average (2).			

### 6.3.4 Summary of implications for practice

Finally, it has been possible to draw some insights from the game to generalize the lesson learned from the game. The insights are aimed to underscore the relationships between the SBCE enablers embedded in the game and their impact on knowledge building, performance improvements, and generally for SBCE successful implementation.

In order to obtain such insights, summated scales (Spector 1992) are developed based on the same questions asked to players in the three learning outcomes (declarative, procedural and strategic). The questions are regrouped, and data sets are aggregated to build theoretically valid constructs. Constructing scales (that have similar theoretical constructs) is an iterative process (Spector 1992). Moreover, the reliabilities of the summated scales are checked using ‘Cronbach alpha ( $\alpha$ )’ coefficients (Cronbach 1951; Cronbach, et al. 2004). Any scale with value of  $\alpha$  more than 0.70 is considered to be reliable (Cronbach 1951; Cronbach, et al. 2004). Below, brief discussion about the scales developed and their inter-correlations are discussed. Furthermore, the implications of the correlations to practice will be discussed accordingly.

#### 6.3.4.1 Definitions of summated scales

Summated scales are widely used in social science to develop a construct that has more meaning than interpreting individual questions posed in Likert based items (Spector 1992). A summated scale must contain

multiple items. The use of summated in the name implies that multiple items will be combined or summed. In the evaluations of the learning outcomes of SBCE game, the questions were addressed individually, as discussed previously in sub-sections. However, to make a general summary of what has been learned from the game, the responses of the questions which have similar theoretical and practical implications are grouped within a scale. To check if a single question belongs to a general scale, the prevalent coefficient of reliability, Cronbach alpha ( $0 \leq \alpha \leq 1$ ) is used (Cronbach 1951; Cronbach, et al. 2004).

The general accepted  $\alpha$  is more than 0.7. This is used to check if a group of questions are measuring the same or similar underlying theoretical construct, or has similar meaningful interpretation for industrial practices. Thus, if adding a question on a scale reduces  $\alpha$  coefficient, it will be removed or assigned to another related scale. Otherwise, either it can be taken as a standalone scale (if it has significant implication as a standalone construct) or it will be discarded from consideration. For example, the data set from the question *S1 (the use of tradeoff and limit curves in future projects)* was rejected because the  $\alpha$  coefficient keep decreasing whenever it is assigned to its logical constructs such as tool or knowledge building. Moreover, it cannot be a standalone scale since it is too narrow to be considered as a scale construct. It is concluded that, the question itself has a problem because of the inclusion of “and” in the statement, which might have confused respondents whether they are answering about the *use of tradeoff curves* or the *use of limit curves*. Since the question has been confusing to respondents, and the inclusion into other scales creates more variation, it is rejected from consideration. Following such a meticulous iterative process the final scales are developed, which have valid implications for practice and theory and have acceptable reliabilities.

Figure 6.13 shows the developed scales that are theoretically valid and have reliabilities ( $\alpha \geq 0.7$ ). There are six scales that are developed and named as: *Tool, Involvement, Communication, Knowledge building, Performance and Implementation*. The first four scales are directly related to some of the SBCE enablers identified and discussed in chapter 4. These enablers are requirements for an SBCE implementation to be effective in product development. In SBCE game some of the enablers are embedded in the game itself and throughout the play (interaction between players and the game facilitators). Of course, there is a clear limitation on gaming to include all the SBCE enablers. Since game design demands simplicity to transfer theoretical concepts in a simplified manner, all the available enablers are not included. Nevertheless, the four enablers that are already embedded give interesting inklings about their relationships within each other, and their correlations with performance and implementation success scales. Below the overviews about the scales are given as follows:

- *Tool (T)*: is a scale that represents one of the SBCE enabler which is embedded in the game play and it is composed of questions D1, D2, S7, D7, and S10. The data set from D1 can be used to understand the respondents understanding and use of the tools embedded in the game as a whole (e.g. tradeoff curves,

checklists and limit curves). The data sets from D2 and S7 can be used to understand the respondents understanding and use of the tools for exploration of alternative designs (e.g. tradeoff curves). The data sets from D7 and S10 can be used to understand the respondents understanding and use of the tools for the convergence process or elimination of alternative designs (e.g. limit curves). In sum, the Tool (T) scale can be defined as the understanding and use of tools in SBCE process.

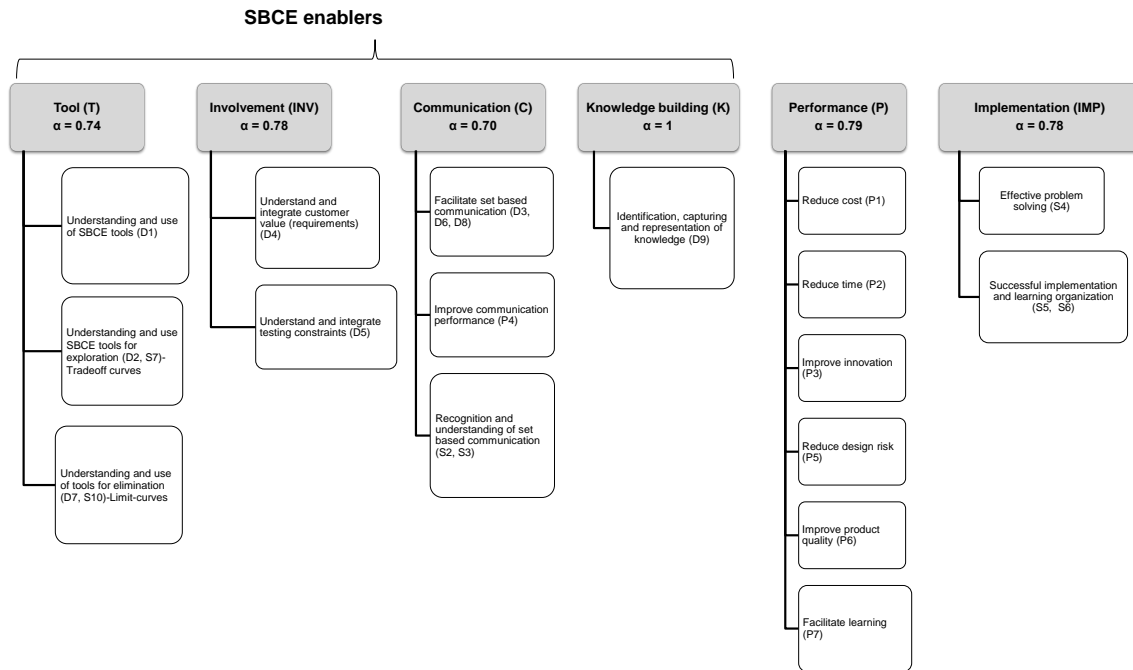


Figure 6.13: Summated scales of SBCE enablers, performances improvements and implementation success.

- *Involvement (INV)*: is a scale that represents another SBCE enabler. Involving stakeholders are taken as a key enabler for SBCE successful implementation. In the game, there are two stakeholders who are simulated in the play (customer as external and testing department as downstream function). The two questions which are summed in the Involvement scale are D4 and D5. D4 takes into account the understanding and importance of capturing and integrating customer value (requirements) in to design and development process. The second one (D5) takes into account the understanding and integrating testing constrains by involving downstream functions (e.g. testing department). In sum, Involvement (INV) scale can be defined as the understanding and integration of stakeholders in SBCE process.
- *Communication (C)*: is a scale representing another SBCE enabler. Communication in SBCE should be based on sets rather than a point based communication. The six Likert based questions summed in this scale are: D3, D6, D8, P4, S2 and S3. The data sets from D3, D6 and D8 indicate the facilitation of principle of set based communication. The data set from P4 represents the performance benefit of

SBCE to improve communication among subsystem teams (body, cockpit, tail and wing). The data sets from S2 and S3 are used to indicate the recognition and understanding of set based communication by industrial players. In sum, Communication (C) scale can be defined as recognition, understanding, and benefit of adopting set based communication.

- *Knowledge building (K)*: is a scale that represents one of the most important enabler of SBCE process. The scale is composed of a standalone question D9. This Likert item question represents the identification, capturing, effective representation of knowledge in SBCE. Thus, the data set from question D9 is used to represent the knowledge building scale. Knowledge building (K) scale, therefore, can be defined as the identification, capturing and representation of design related knowledge in SBCE process.
- *Performance (P)*: this scale does not represent any SBCE enabler. But, it is the impact of the SBCE enablers (embedded) in the game on perceived performance improvements. It is composed of all the performance measures discussed in procedural learning outcomes earlier, except P4. P4 (improve communication) is grouped under Communication (C) scale; because  $\alpha$  has decreased drastically when it is grouped in performance (P) scale. Therefore, the logical scale to put P4 has been on Communication (C) scale. Thus, Performance (P) scale is composed of the data sets from questions P1, P2, P3, P5, P6 and P7. And, it can be defined as the performance improvement potentials of the SBCE enablers such as Tools (T), Involvement (INV) and Communication(C) and Knowledge building (K).
- *Implementation (IMP)*: this scale is to measure the success of SBCE implementation. Once a company adopts the enablers of SBCE and obtain some performance improvements, then the company can say that SBCE has been successful implemented. The three questions grouped in this scale are: S4, S5 and S6. Data set from S4 represents the ability of designers and managers in solving problems using the SBCE enablers (embedded in the game). Data sets from questions S5 and S6 represent the successful implementation of SBCE and the capacity to become a learning organization using the SBCE enablers. Thus, Implementation (IMP) scale can be defined as the capability of a company to be adept in problem solving and becomes a learning organization.

#### **6.3.4.2 SBCE enablers, performance improvements and implementation success**

To test if there are significant correlations between the SBCE enabler scales (T, INV, C, and K), perceived performance improvements scale (P), implementation success scale (IMP), a non-parametric test is used. Since the data are based on ordinal (Likert) items, the most appropriate and prevalent correlation coefficient

to use is Spearman's rho ( $\rho$ ) (Siegel 1957; Newson 2001). Moreover, STATA 2010 statistical package is used for data analysis, and to find the  $\rho$  coefficients and tests for the significant levels of the correlations.

Table 6.13 and Figure 6.14 show the results of the correlations between the scales and their significant levels (p-values). As shown from the results, according to the industrial game players, the SBCE enablers have strong correlations with each other and contribute significantly to performance improvements, as well as to bring the design organization to a successful learning organization.

Table 6.13: Correlations between SBCE enablers, perceived performance improvement and implementation success ( $N=49$ ,  $(\#) p \leq 0.10$ ,  $(*) p \leq 0.05$ ,  $(**) p \leq 0.01$ ).

Spearman rho ( $\rho$ ) for model correlation						
	T	INV	C	K	P	IMP
T: the understanding and use of tools in SBCE process	1.0					
INV: the understanding, and integration of stakeholders in SBCE process	0.4581 <sup>(**)</sup> (0.0009)	1.0				
C: the recognition, understanding, adoption of mechanisms and techniques that facilitate set based communication in SBCE process	0.3866 <sup>(**)</sup> (0.0061)	0.2452 <sup>(#)</sup> (0.0894)	1.0			
K: the identification, capturing, and representation of knowledge in SBCE process	0.5548 <sup>(**)</sup> (0.0000)	0.4521 <sup>(**)</sup> (0.0011)	0.2042 (0.1593)	1.0		
P: the performance improvement potentials of the SBCE enablers	0.4584 <sup>(**)</sup> (0.0009)	0.3806 <sup>(**)</sup> (0.0070)	0.3540 <sup>(*)</sup> (0.0126)	0.3635 <sup>(*)</sup> (0.0103)	1.0	
IMP: the capability of a company to be adept in problem solving and become a learning organization using the SBCE enablers	0.4833 <sup>(**)</sup> (0.0004)	0.5268 <sup>(**)</sup> (0.0001)	0.3378 <sup>(*)</sup> (0.0176)	0.4304 <sup>(**)</sup> (0.0020)	0.5183 <sup>(**)</sup> (0.0001)	1.0

Tool (T) for example, has significant ( $p \leq 0.01$ ) correlations with all other enablers INV, C and K, and with  $\rho$  coefficient values of correlation 0.4581, 0.3866, and 0.5548 respectively<sup>20</sup>. The results show that tools and methods (e.g. limit curve, tradeoff curves, and checklists) as enablers contribute to facilitate set based

<sup>20</sup> For the sample size  $N=49$ , the minimum threshold for correlation  $\rho$  is approximated to be 0.235, 0.279 and 0.365 for two-tailed significance p-levels of 0.10, 0.05 and 0.01 respectively (Newson 2001).

communication (C), to have effective involvement with stakeholders (INV) and build knowledge (K) in SBCE process. Moreover, except Communication (C), Tool (T) and Involvement (INV) significantly contribute for knowledge building (K) with significant level ( $p \leq 0.01$ ), and with  $\rho$  coefficient of correlations 0.5548, 0.4521 respectively.

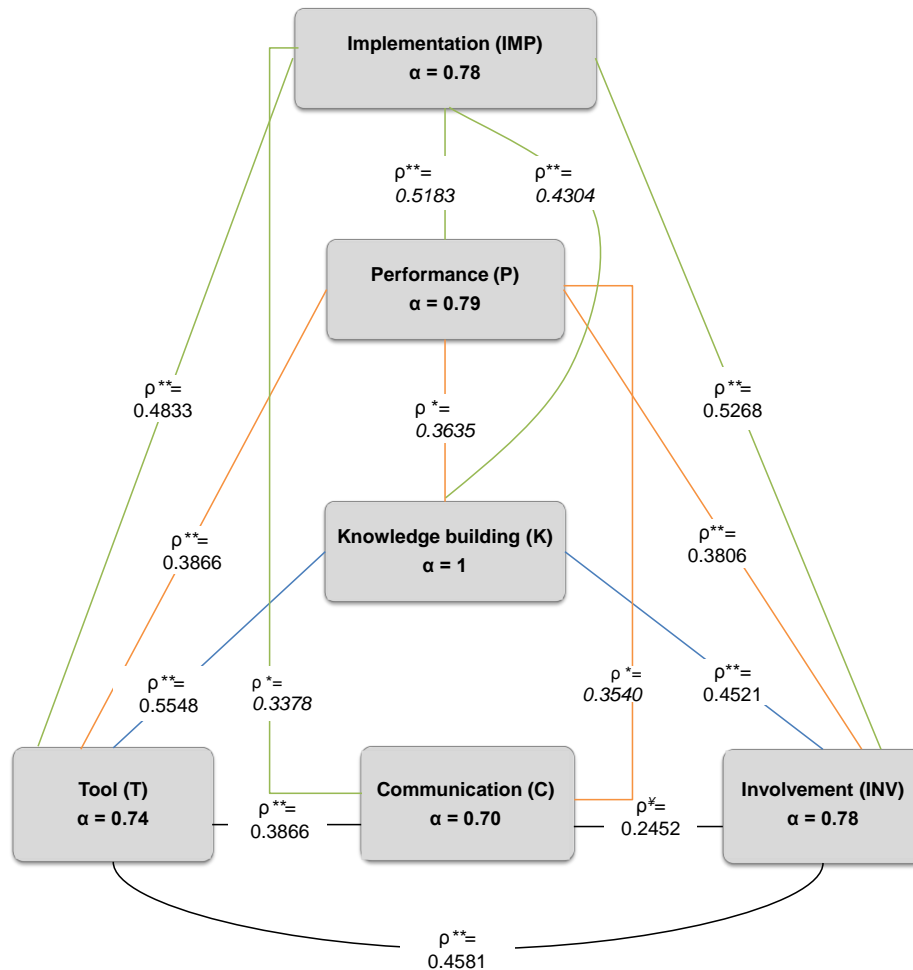


Figure 6.14: Correlations between SBCE enablers, performance and implementation success ( $N=49$ ,  $p \leq 0.10$ ,  $(*) p \leq 0.05$ ,  $(**) p \leq 0.01$ ).

From the results observed in Figure 6.14, Communication (C) doesn't have a significant correlation with Knowledge building (K). However, the results from previous studies have shown mixed relationships about the two. For example, Sobek et al. (1999) conducted a detail observation on the communication style between Toyota and its suppliers. They have found that, suppliers of Toyota communicate in ranges and also develop several prototypes for the same design concept. Toyota requests the suppliers to communicate in this style. The rationale behind is that, Toyota wants to understand the underlying tradeoffs between alternative designs (Ward, et al. 1995; Sobek, et al. 1999). The set based communication style between Toyota and its

suppliers is used to build tradeoffs between performances of alternative designs. This relationship is helping to build knowledge about design performances in the form of tradeoffs. Thus, this study shows that set based communication has at least a positive relationship with knowledge building (Sobek, et al. 1999; Ward, et al. 1995).

On the other hand, Liker et al. (1996) survey study shows a different result. Liker et al. (1996) conducted a detail survey study about SBCE on US and Japanese automakers. The result shows that, set based communication has been considered as a negative practice by some industries. Except Toyota and some Japanese OEMs, US manufacturers use 'single best guess' (point based communication) rather than 'ranges or alternatives' (set based communication) to communicate with customers and suppliers. In particular, the US manufacturers use one design solution to communicate with their suppliers. The survey showed that, US manufacturers consider the communication of ranges and alternatives with suppliers as 'undecided'. That is, they don't want to present unfinished requirements to suppliers, as if they are not sure what they requesting. This kind of relationship with suppliers help US manufacturer to control quality and cost targets. Otherwise, suppliers might abuse the relationship taking the set based communication as a leap for bad performances. Moreover, US manufacturers who use ranges don't elongate the communication for a longer period. Rather, they freeze the requirements early in the beginning. Therefore, the above discussion shows that set based communication is not always taken as a means of building knowledge (e.g. for tradeoff analyses), rather point based communication is referred to make faster decisions and control cost targets.

Coming to the case company and the SBCE game, the result shows that there is no significant relationship between set based communication and knowledge building. The sample size (N=49) in the game is small to generalize the result. However, the game play was conducted in an industrial context where the nature of product development is different from Toyota or any other big automakers. The insignificant relationship between set based communication and knowledge building might mean different for this particular case or might be related to the tendency to use point based communication as a cost control mechanism (similar to most US manufacturers).

Other possible reasons can also be mentioned to cipher the possible rationale behind the results. First, one might guesses that, the relationship between set based communication and knowledge is not well understood by players. Second, communication in sets might be less important for the case company as a way of knowledge building mechanism. This second reason has also been implied and discussed previously during the measurement of declarative learning (see section 6.3.1.1). This might be related to the nature of the products the case company designs, which don't involve large numbers of sub-systems that demand set based communication and tradeoff analyses to capture/build knowledge. Moreover, since few internal designers and external suppliers involved in a project, set based communication based on ranges and alternatives might

not be significant source for knowledge building. Or, as in some cases, a single designer is responsible to design a new project where the knowledge is centralized by few individuals making knowledge building in the form of tradeoff curves or any other extensive knowledge capturing mechanisms less efficient.

In summary, from Figure 6.14, one can easily understand that SBCE process is a journey. It takes time to get successful results and become a learning organization. The understanding and use of the tools necessary for communication, involvement and knowledge building are the primarily steps to start the SBCE journey. Once the tools are effectively embedded in product development, SBCE fosters communication and facilitates effective involvement of stakeholders in SBCE implementation process. Then, the company can identify, capture and reuse market and technical knowledge. Once knowledge is effectively shared across projects and across design teams, performance improvements can be seen as a result of the SBCE implementation efforts. Finally, one can say that, SBCE implementation is successful and a company becomes a learning organization, who can dynamically design products in a knowledge base environment.

## **6.4 Conclusions, limitations and future researches**

The purpose of this chapter was to fill the gap that exists across many industries; there has been a lower awareness level of SBCE. As discussed in section 5.2.2, most companies that have been surveyed have exhibited lower level of understanding on what and how SBCE process works and previous researches also indicate similar gap. However, at the same time there are growing interests from industries to know and adopt it in practice. Therefore, filling this gap has been taken as one objective in this thesis.

In order to fill the gap, the SBCE serious game has been developed. Gaming has been chosen as an approach because of its ability to transfer complicated concepts into simplest forms. Moreover, game has been effective to bring a hand-on experience for industrial practitioners about SBCE process that has been new to most industrial players, in a safe environment and entertaining manner.

The game has been played by more than 60 designers and managers (49 responses) working in one company. The learning outcomes from the game have been assessed using Garris model (Garris, et al. 2002). The players' understanding about the SBCE principles and enablers, the perceived performance improvements of the principles and enablers are measured (declarative and procedural learning). Moreover, players' tendencies to adopt what they have trained in the game to practice also have been one of the focuses of the measurement of the learning outcomes (strategic learning).

From the game measurements, interesting results that have important reflections for the theory and practices of SBCE process have been found. In particular, the results have significant implications for small and medium sized companies. Moreover, a simplified roadmap has been proposed to stress the fact that SBCE is



a journey, which starts with implementing SBCE enablers. SBCE enablers such as tools, communication and involvement are the first steps that should be implemented before one seeks knowledge building and performance improvements. Moreover, once the preliminary enablers are effectively embedded in a development organization, SBCE is a paradigm that foster knowledge building, performance improvements, and further succeed in its implementation. Table 6.14 summarizes the summaries of results from the game measurement, the rationales and the implications for practice and theory.

There are limitations on the research and consequently on the results found. Although, the SBCE game has been a success in this particular company, it needs to be introduced to wider industrial players in different contexts. Moreover, the conclusions and implications discussed in this chapter are predominately based on the feedbacks from one company which specializes in HVACR market. If different industrial types are included a more solid and accurate results concerning the applicability of SBCE in industries can be developed. Therefore, future researches remain to validate the game with different other industrial players and compare the results across industries.

There are also limitations related to the design of the SBCE game. The current version of the game contains only certain enablers of SBCE process. However, as discussed in chapter 4, there are other enablers that are interesting to be included (e.g. organizational aspects, people competences, chief engineering system and so on). Therefore, more researchers remain both in the game design and measurement/validation aspects.

The second part of this thesis is presented in the next chapter 7. This chapter address the second research gap identified (the lack of a methodological approach to identify and prioritize areas for SBCE implementation at a product level). The extensive nature of SBCE rationalizes the need for a systematic methodology to lead designers to focus the efforts. The extensiveness of SBCE has also been observed from the feedbacks obtained for SBCE serious game. This thesis proposes a methodology called SBCE IR to address this gap. Moreover, in chapter 7 the discussions on the validation of the SBCE IR methodology are presented.

Table 6.14: Summaries and conclusions of the results of SBCE serious game measurement.

Learning outcomes	Results obtained from game measurement and feedbacks from industrial players	Rationales	Implications for practice and theory
<b>DECLARATIVE LEARNING OUTCOMES</b>	SBCE serious game has been effective to introduce SBCE's principles and enablers embedded in the game.	<ul style="list-style-type: none"> <li>The game is designed to educate SBCE and comparison between PBCE is made. Tradeoff curves, checklists and limit curves have been embedded in the game to facilitate the SBCE in designing a simplified airplane structure.</li> </ul>	<ul style="list-style-type: none"> <li>The game can be used to educate practitioners to increase their awareness level about SBCE.</li> </ul>
	Principle of set based communication and tools to facilitate it might not be critical in this company.	<ul style="list-style-type: none"> <li>Products in HAVC/R market do not involve complex and integrate subsystems like automotive designs (where set based communications is key).</li> <li>Small design team members for a design project.</li> <li>Difficulties of communicating design sets with suppliers.</li> </ul>	<ul style="list-style-type: none"> <li>Set based communication might not be a key principle of SBCE when: there is no- design complexity, number of designers in a project is very small and when suppliers are not willing or capable of communicating in sets.</li> </ul>
	Designers and managers have different level of understanding of SBCE as presented in the game. Managers have higher awareness of SBCE than technical designers.	<ul style="list-style-type: none"> <li>Managers have pre-information about SBCE from reading lean product development books, attending seminars and conferences.</li> <li>Managers have more ambitions for change.</li> </ul>	<ul style="list-style-type: none"> <li>If the differences arise because managers are pre-aware about SBCE, that will cause less problem during a real implementation phase.</li> <li>However, if the differences arise from "cultural" issues, that is, if designers don't appreciate new way of working than the norm, then, it will be difficult for managers to disseminate the concept of SBCE and obtain a wider acceptance in the company.</li> </ul>
	There is a significant	<ul style="list-style-type: none"> <li>Less experienced designers in the company indicated</li> </ul>	<ul style="list-style-type: none"> <li>Experience matters to understand and effectively deploy SBCE.</li> <li>Tools used in SBCE serious game</li> </ul>

	<p>difference between highly and less experienced players in perceiving SBCE.</p>	<p>that there are difficulties to anticipate design problems at the frontend of a design project, and the SBCE tools provided in the game has been appreciated to alleviate this problem.</p> <ul style="list-style-type: none"> <li>• Highly experienced players also indicate the importance of adopting SBCE tools to capture and transfer their knowledge to less experienced designers.</li> </ul>	<p>has been perceived as very important to capture knowledge and knowhow and further transfer to less experienced designers.</p>
<b>PROCEDURAL LEARNING OUTCOMES</b>	<p>Industrial players have perceived significant benefits of SBCE in improving performances such as: reduction of risks, reduction of product/process costs, facilitates learning, improving quality.</p>	<ul style="list-style-type: none"> <li>• The SBCE serious game provides a performance measurement scheme to compare PBCE and SBCE. During the play significant performance improvements have been demonstrated.</li> <li>• Players have also give feedbacks on the performance benefits of SBCE if it is applied in their real design practice.</li> </ul>	<ul style="list-style-type: none"> <li>• SBCE is beneficial for industries in improving performance measure of product development.</li> </ul>
	<p>SBCE as portrayed in SBCE game or in literature has a limitation in enhancing innovation.</p>	<ul style="list-style-type: none"> <li>• Innovation is perceived by the industrial players as an achievement of new design solutions which are unexpected.</li> <li>• However, the use of tradeoffs in SBCE as an exploration tool restricts the level of innovation. Because tradeoffs are based on accepting compromise rather than advancing performances to new levels.</li> <li>• Moreover, generating tradeoffs are difficult in practice.</li> </ul>	<ul style="list-style-type: none"> <li>• If tradeoffs are used for exploring alternatives in SBCE, it might limit the level of innovation that can be achieved. Therefore, exploration of concepts or generation of ideas has to been supported by other established innovation theories such as TRIZ to enhance innovation in SBCE process.</li> </ul>
	<p>Managers have higher perception</p>	<ul style="list-style-type: none"> <li>• Managers have more tendencies to accept SBCE</li> </ul>	<ul style="list-style-type: none"> <li>• Managers should convince technical personnel on the real value of SBCE either by taking</li> </ul>

	on SBCE's potential benefits for performance improvements than technical designers.	<p>as performance enhancer.</p> <ul style="list-style-type: none"> <li>Managers have more ambitions for change.</li> </ul>	<p>pilot projects or introducing them with success stories from other industrial cases.</p>
<b>STRATEGIC LEARNING OUTCOMES</b>	Thanks to the game, most practitioners are willing to adopt SBCE in their design practice.	<ul style="list-style-type: none"> <li>Most players acknowledge that playing the game has been worthwhile for their design practice</li> <li>Most players acknowledge that playing the game help to have ideas on how to practice SBCE enablers embedded in the game.</li> </ul>	<ul style="list-style-type: none"> <li>The game has been effectiveness in convincing players to adopt it in their daily practice.</li> <li>The game also helps on giving ways in how practitioners can execute SBCE in practice.</li> </ul>
	Generating tradeoff and limit curves are challenging in practice.	<ul style="list-style-type: none"> <li>Companies like this have limitations in resources to invest on simulation and testing tools to generate tradeoffs and limit curves. Moreover, generating alternative designs and building prototypes in parallel will be costly for these companies to capture and analyze governing performances data about sets.</li> </ul>	<ul style="list-style-type: none"> <li>SBCE should be taken as a process and as a journey where knowledge is systematically captured as a long term strategy. Developing tools, involving stakeholders, and effective communication should be in place to build knowledge. Then, performance benefits can be shown as a result and companies can successful implement SBCE and develop products in a knowledge based environment.</li> </ul>
	Managers have higher interests to adopt SBCE than technical designers.	<ul style="list-style-type: none"> <li>Managers have more ambitions for change and implement new concepts.</li> </ul>	<ul style="list-style-type: none"> <li>Care should be taken by managers before going to real implementation of SBCE and should obtain organization-wide awareness about the benefits of SBCE.</li> </ul>
	There is significant difference between highly and less experienced players in their ability to adopt SBCE in practice.	<ul style="list-style-type: none"> <li>Less experienced designers need coaching and mentoring on how to explore, communicate and evaluate sets. In playing the game, less experienced layers indicated challenges for them to adopt SBCE in their design practice.</li> </ul>	<ul style="list-style-type: none"> <li>Competence development is very important before implementing SBCE in practice. Highly experienced designers should do coaching and mentoring on how to conduct SBCE to less experienced engineers.</li> </ul>

<b>SUMMARY OF DECLARATIVE, PROCEDURAL AND STRATEGIC LEARNING OUTCOMES</b>	SBCE enablers such as tools, involvement, and communication are significantly correlated.		<ul style="list-style-type: none"> <li>• Tools such as tradeoff curves, checklist and limit curves helps in SBCE to effectively involve stakeholders (customers and internal function e.g. testing department). Moreover, the tools help to facilitate communication between subsystems departments to evaluate sets for compatibilities and feasibilities issues.</li> </ul>
	Except set based communication, SBCE enablers such as tools, involvement are significantly correlated with knowledge building.	<ul style="list-style-type: none"> <li>• Set based communication has been perceived less significant in the case company as knowledge building mechanism because of: few designers are involved in new projects and knowledge is centralized in few experts. Furthermore, price based relationships with suppliers dictates point based communication.</li> </ul>	<ul style="list-style-type: none"> <li>• For set based communication to commence in practice, trust between suppliers or partners should be build, so that sets can be explored and communicated.</li> <li>• Price based relations between developers and partners restrict the level of sets to evaluate and limit the possibility to discover and develop knowledge about the performance of alternative solutions.</li> <li>• When few or one designer is responsible for a project (common in smaller companies) tools to enable set based communication with team members to evaluate sets might not be important.</li> </ul>
	Implementation of SBCE should be taken as a journey.		<ul style="list-style-type: none"> <li>• In order to improve performance using SBCE enablers, the understanding and adoption of SBCE enablers are important. But, it needs efforts and investments to effectively build an organization that manage and share knowledge to develop products.</li> </ul>



## 7 METHODOLOGY FOR IDENTIFYING AND PRIORITIZING AREAS TO APPLY SBCE

This chapter is dedicated to address the second part of this thesis. As discussed in more details in chapter 5, section 5.2, whenever a SBCE implementation is planned at a product level, one question to address is related to where in a product system SBCE efforts should focus. SBCE is an extensive process. It demands a rational and careful investigation a priori to identify where SBCE should be applied and use it to benefit customers with better product and increase value to the company. Otherwise, random efforts made on SBCE might be wasted without achieving the desired value. This thesis proposes a systematic methodology called SBCE Innovation Roadmap (SBCE IR) to help product developers to identify and prioritize improvement areas to begin SBCE processes at a product level. In this regard, the SBCE IR promotes incremental SBCE implementation at subsystem or component levels rather than full system level innovation. The methodology is based on identifying, prioritizing and mapping contradictions. The SBCE IR consists of six steps. Each step is supported by prevalent tools and methods. Moreover, the methodology is validated using a case study on AHS (Adiabatic Humidification System). The humidification system is a product that is used primarily for industrial. Furthermore, using the roadmap built for AHS, a Rack subsystem is selected to show how to use SBCE IR as an input for SBCE process and further arrive into innovative Rack design. New Rack has been design where significant cost reduction is anticipated. Finally, open questionnaire is prepared and interviews are made with the designers and product managers of AHS to validate the advantages and limitations of the SBCE IR. In general, the SBCE IR is considered by the experts to be useful to better structure innovation process, to effectively plan SBCE improvement projects and facilitate innovation. The following limitations also are identified: it takes time to build SBCE IR; it might not be stable if customer requirements are changing frequently; and skills/ expertise are required to build it.

## 7.1 Introduction

In this section the discussion continues in briefing the central concept of SBCE IR by elaborating on why the SBCE IR methodology takes contradictions as a central concept to build the innovation roadmap. Moreover, this section extends the discussions on the criteria and assumptions considered in constructing SBCE IR.

In section 7.2, introduction of the SBCE IR is presented and its steps are discussed. Further in section 7.3, the validation of the SBCE IR on the AHS case study is presented. The SBCE process conducted on Rack subsystem as well as the assessment of the methodology by experts are parts of section 7.3. Finally, conclusions, limitations and future researches of part two of this thesis are presented in section 7.4.

### ***7.1.1 Contradictions, trade-offs and SBCE***

SBCE IR is based on identifying and prioritizing contradictions. Therefore, this section is dedicated to the discussion on why contradictions are taken as key concept to build the innovation roadmap. Further in section 7.1.2, the criteria used and the assumptions taken are discussed and rationalized.

‘Contradiction’ is a word taken from TRIZ body of knowledge (see section 4.6 for more details on TRIZ). The term implies conflicts between requirements (called technical contradictions) or conflict within a requirement (physical contradictions).

As discussed in section 4.6 of this thesis, the prominent Russian scientist used the term contradiction after investigating large number of genuine inventions along his carrier at a patent office. His observation underscores the fact that most genuine innovations that were successful follow similar patterns. Moreover, majority of good inventions or new design concepts are generated while solving or overcoming contradictions (Altshuller 1984).

Considering SBCE, which originates from the practices of Japanese automakers (Toyota in particular) has strictly been related to use of performance trade-offs in extant literature. Toyota, for example, reported to base on trade-off analyses for exploring, evaluating and communicating about sets of solutions (Sobek, et al. 1999).

A note to take into account here is the difference between contradictions and tradeoffs. Conceptually, contradiction and tradeoff explain the same underlying issue. Whenever one identifies a contradiction in a product system, inherently can identify the governing tradeoff related to that contradiction. Taking a very simple example, a material might be required to have a higher strength for safety and at the same time the material might be required to have less mass for fuel efficiency. In this case, safety and fuel efficiency are in

tradeoffs or are in technical contradiction<sup>21</sup> (one cannot increase safety without sacrificing on fuel efficiency or vice versa). However, the differences between contradiction and tradeoff arise when one proceeds to generate design solutions. In particular, the following considerations are important for this thesis:

- a) *The use of trade-offs in SBCE restricts innovation*: established theories of innovation in design argue that using and accepting trade-offs restricts the level of innovation (Altshuller 1984; Hua, et al. 2006; Sheng and Kok-Soo, 2010). Altshuller, underscores the limitation of accepting trade-offs in design (Altshuller 1984, 1994, 1999; Hua, et al. 2006). Taking the previous material choice example, a designer might investigate alternative materials that have different performances on safety and fuel efficiency, and make an optimal tradeoff to select a material that has average values for the two performances. In TRIZ, however, trade-offs or compromises are not accepted, rather they are eliminated if innovative design solutions are sought to be discovered. In our material choice example, the designer might use the TRIZ principle of ‘separation in parameter (Altshuller 1984)’ to design a material that has high safety performance and high fuel efficiency when needed, and push the existing technology performance curve. Figure 7.1 shows the difference between the two approaches with the simplified example. Moreover, in practice, understanding design trade-offs is often too complex and demands extensive efforts to generate (Rossi, et al., 2011/b). This challenge is also exhibited from the feedback obtained from practitioners in Carel Industries after playing the SBCE serious game (see section 6.3.3.2). Thus, SBCE has to be discussed along with established theories of innovation both to simplify it and enhance innovation. If TRIZ is integrated with SBCE process, there will be significant methodological benefits in identifying potential areas for design improvements (Bhushan 2007). The proposed SBCE IR methodology integrates the concept of contradictions in TRIZ to identify areas where SBCE can be implemented. That is, different SBCE processes can be launched to overcome different contradictions.
- b) *‘Psychological inertia (PI)’*: is another practical challenge to do the first principle of SBCE (mapping design space or principle of exploration). PI is a phenomenon in design practice where designers often tend to explore solutions within known design spaces (Kowalick, 1998). In particular, considering that 80% of new design projects are based on minor or small improvements from existing technologies and within a given tradeoff curve, it often becomes unlikely for designers to observe ‘out of the box’ or innovative solutions (Morgan and Liker 2006; Altshuller 1984, 1994). The feedback from the SBCE serious game also indicates this drawback of SBCE (see section 6.3.2.2). Although, the SBCE IR doesn’t have a direct contribution to avoid the

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<sup>21</sup> In this example, the contradiction can also be expressed as physical contradiction. The weight of a material should be high for safety and the weight should be low for fuel efficiency. In most cases technical contradictions can be converted to physical contradictions and vice versa (Kalevi and Domb 2008).



phenomena, it allows design problems to surface as contradictions, and the prevalent TRIZ's principles<sup>22</sup> [e.g. the separation principles, the 40 inventive principles, etc. (Altshuller 1984, 1994; Savransky 2000))] can further be used to explore innovative solutions to start SBCE process.

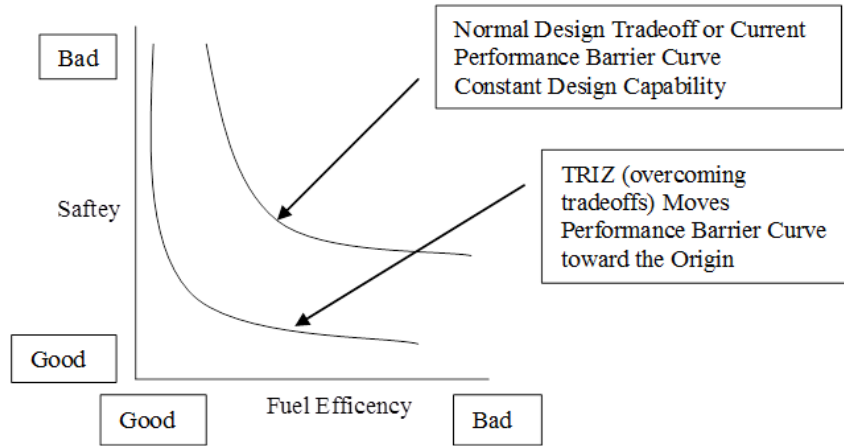


Figure 7.1: Difference on accepting and overcoming trade-offs (modified from Hipple 2003).

### 7.1.2 Criteria and assumptions considered

The following criteria and related assumptions are considered while building SBCE IR:

- a) *The process of overcoming contradictions will follow SBCE process:* in constructing the SBCE IR it is assumed that identifying contradictions leads to improvement areas where SBCE can be applied. Moreover, once contradictions are identified in a system, SBCE processes will follow to overcome the contradictions. Meaning, contradiction will be inputs to SBCE processes. The principles and process of SBCE (exploration, set based communication and convergence) is followed to arrive into a high value solution that overcomes the contradiction identified. Of course, TRIZ's principles can support the first principle of SBCE (exploration) to bring innovative conceptual solutions and reduce the human effect of psychological inertia. SBCE principles of communicating sets and testing before commitment enrich the process and reduce the risk of late design changes due to incompatibility and infeasibility issues. Thus, SBCE IR benefits from the synergies between TRIZ and SBCE principles. However, this assumption fails if designers use PBCE to overcome a contradiction and consider only one conceptual solution and proceed developing it.

<sup>22</sup> TRIZ principles are very effective to tackle Psychological Inertia (Altshuller 1984, 1994; Kowalick, 199; Savransky 2000). Moreover, following these TRIZ's principles will formalize the search efforts to find design solutions in SBCE.

- b) *The area of improvements should be valuable for the customers:* this indicates that the SBCE implementation efforts should take into consideration the right customer value or requirements. It is not uncommon that designers spent considerable amount of their time developing features that the customers are not really interested in (Bauch 2004; McManus 2004; Kato 2005; Pessoa, et al. 2008; Rossi, et al. 2011/b). Thus, information on customer value is paramount to be integrated before starting on a particular SBCE process. Once contradictory requirements are identified, customers' judgment on importance can be used as one criterion to prioritize contradictions (i.e. how significant for customers will be if a contradiction is solved?).
- c) *The area of improvements should give competitive advantages for the company through offering a better product than competitors:* customers are not always right, or sometime they don't even know what they want today and in the future. Thus, basing the SBCE efforts solely on customers can not entirely show the opportunities available for improving a product system. Often, new requirements, ideas and innovation potentials arise from competitors, technology trends and internal brainstorming. Thus, while building the SBCE IR, competitor analysis is used as an additional criterion to prioritize contradictions (i.e. how important will solving a contradiction be for competitiveness?).
- d) *The area of improvements should be achievable with respect to the resources available:* once improvement areas of contradictions are discovered, some need more resources to overcome and advance the existing technology. Some other need small improvements. So, SBCE application needs different approaches for different levels of improvements. For contradictions that need less resources, it is logical to plan narrow SBCE processes, where designers explore better design solutions within known design-spaces (e.g. searching for alternative components/materials or production routes and so on). Such SBCE initiatives shouldn't take much resources in terms of time and investment. However, for contradictions that need considerable resources to overcome, wider SBCE processes should be planned where designers might need to explore solutions by substantially changing the product's structure and functions. Wider SBCE implementations, therefore, need considerable amount of resources. Differentiating the type of design improvements at hand is crucial to understand what kind of SBCE process to pursue. A narrow SBCE process is convenient to be conducted in a Takt development process, where there is a strict schedule control on time and cost measures. However, it is more convenient to conduct a wider SBCE process in a non-Takt process (e.g. at R&D level), where there is no strict schedule control to respect

delivery time and development cost<sup>23</sup>. The SBCE IR doesn't explicitly consider resources needed as criterion to prioritize contradictions for SBCE. However, experts should take this into account while planning SBCE projects to overcome prioritized contradictions.

## 7.2 Introduction to SBCE Innovation Roadmap (SBCE IR)

Six steps are needed to build SBCE IR for a product as shown in Figure 7.2. These are: (1) Identify customer requirements and assign importance, (2) Assess competitors' products and set targets, (3) Identify system contradictions, (4) Identify causal contradictions, (5) derive rules to prioritize contradictions and (6) map contradictions to design factors<sup>24</sup>. After completing the steps, designers will have ranked contradictions to plan and pursue SBCE processes to overcome the contractions.

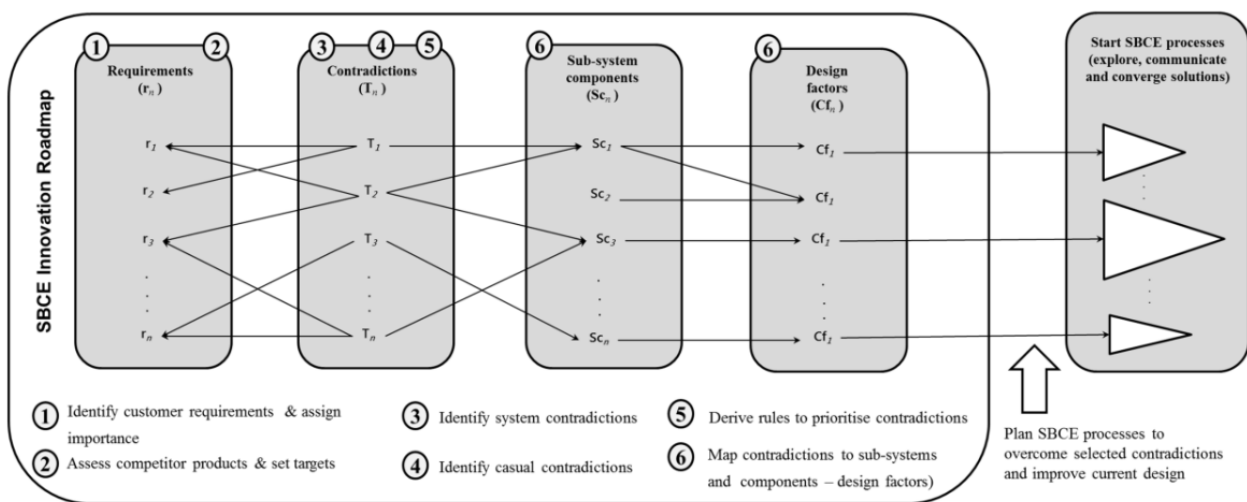


Figure 7.2: Schematic representation of SBCE IR steps.

The steps are facilitated by prevalent logics, methods and tools. In order to have a panoramic view of the steps and simplify the execution of the steps for designers Quality Function Deployment (QFD) tool is used. QFD uses a matrix called the House of Quality (HOQ), which is utilized for the aim of converting market, technical and business information into product design strategies (Hauser and Clausing 1988; Akao and

<sup>23</sup> This consideration is based on the observation during the case study, where some contradictions although have high priorities than others, overcoming them need redefining the product structure and functions. Moreover, there is no guarantee that solutions can easily be found, or might need strong collaboration with stakeholders (e.g. suppliers) to bring new technological advancements. Thus, in this type of situation, research based development at R&D level is recommended.

<sup>24</sup> Design factors could be subsystems, components and associated properties that designers have to change to overcome contradictions. For example, material type of a component, number of components to use, configuration types, etc.

Mazur 2003). Figure 7.3 shows an example of the HOQ excerpted from the case product to facilitate the discussions on the steps of the SBCE IR.

### 7.2.1 Identify customer requirements and assign importance

The first step of the methodology is to capture customer value in terms of requirements. Moreover, evaluating and assigning importance or weight to each identified requirements. The requirements are classified into two: macro and micro requirements (see Figure 7.3). Macro requirements ( $r_i$ , where  $i = 1, 2, 3, \dots, n$ ) are general characteristics of a product that should be fulfilled to satisfy the users. For each macro requirement detail characteristics are defined as micro requirements ( $r_j$ , where  $j = 1, 2, 3, \dots, n$ ).

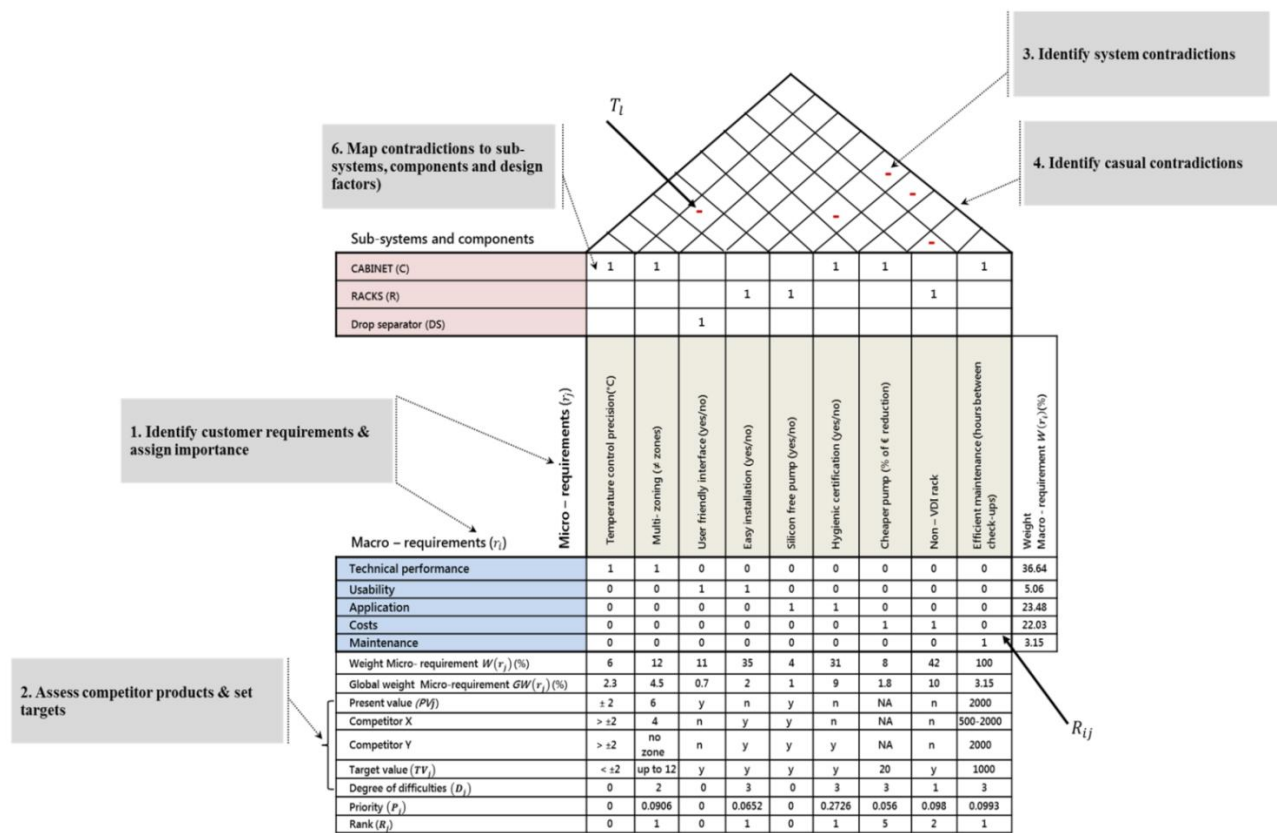


Figure 7.3: An example of House of Quality (HOQ) and the steps to build the SBCE IR (excerpt from the AHS case study, and note: n = no, y = yes, NA = data not available).

The relationships between the macro and micro requirements are given by a matrix  $R_{ij}$ , which indicates the categorization of micro requirements into the general classification (macro) requirements (see Figure 7.3). The relationship can take a value of either 0 or 1 (0 shows no relationship and 1 shows a relationship). This classification helps to represent customer data in a logical manner and simplifies data analyses.

In order to assign importance or weights, macro and micro requirements are treated separately. First, the weights of macro requirements  $W(r_i)$  are determined. Then, the weights of the micro requirements are  $W(r_j)$  determined. To obtain an aggregate global importance  $GW(r_j)$  of a micro requirement Equation 1 is used (Yamashina, et al. 2002):

$$GW(r_j) = W(r_j) * \left( \sum_{i=1}^I W(r_i) * R_{ij} \right) \quad \text{Equation 1}$$

To determine  $W(r_i)$  and  $W(r_j)$ , Analytical Hierarchical process method (AHP, Saaty 1980) is used, which is based on pairwise comparison of requirements. AHP simplifies the understanding of customer requirements, avoids errors in judgment and structures the evaluation of requirements from customer perspective (Van de Poel 2007). The pairwise comparison process in AHP consists of three main sub-steps (Saaty 1980): (a) building judgment matrix, (b) evaluating weights and (c) checking consistencies.

*(a) Building judgment matrix*

In this step, experts such as designers, marketing personnel and others make judgments about the importance of a requirement compared with other requirements. The experts, of course, need to have good understanding of what the customers really want. Otherwise, customer survey or some other customer value research methods have to be used to make judgments about of customer requirements. The experts will be asked to assign importance judgment between two requirements based on the scales listed in Table 7.1 below. Note that, the judgment should be conducted at two levels: macro and micro levels. At macro level, experts will be asked to assign importance scale between two general requirements. For example, between *usability of a product* vs. *product cost* (see Figure 7.3 above). However, to assign importance judgment for micro requirements, experts will be asked to assign scales between two specific micro requirements which are categorized within a macro requirement. For example, referring to Figure 7.3, *temperature control precision* and *multi-zoning* are two micro requirements which are grouped under the macro requirement *technical performances*. Thus, experts will put a judgment scale between *temperature control precision* and *multi-zoning* to reflect the customer importance.

Using the scale, judgment matrices can be built for both macro and micro requirements. Given n numbers of macro or micro requirements  $\{r_1, r_2, \dots, r_n\}$ , decision makers (in this case product designers) compare pairs of the requirements for all the possible pairs, and comparison matrices of judgments  $A_{n \times n}$  are obtained as shown in in Equation 2.

Table 7.1: The pairwise comparison scales (Saaty 1980, 2001, 2008).

Intensity of importance	Definition	Explanation
1	Equal importance	Two requirements contribute equally to the customer
3	Moderate importance	Customers slightly favor one requirement over another
5	Strong importance	Customers strongly favor one requirement over another
7	Very strongly	A requirement is favored very strongly over another
9	Extreme importance	The customers favoring one requirement over another is of the highest possible order of affirmation
2,4,6,8		Intermediate values

Any element  $a_{iq}$  of the matrices (where  $i = 1, 2, 3, \dots, n$  and  $q = 1, 2, 3, \dots, n$ ) is within the scales defined (1/9, 1/8... 8, 9). Taking macro requirements, for example, improving *technical performance* might be judged as 3 time favored than reducing *cost of a product* and  $a_{iq} = 3$ .

$$A = [a_{iq}] = \begin{bmatrix} 1 & a_{12} & \dots & a_{1q} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2q} & \dots & a_{2n} \\ \vdots & 1/a_{2q} & \dots & a_{iq} & \dots & a_{in} \\ \vdots & 1/a_{2n} & \dots & 1/a_{in} & \dots & 1 \end{bmatrix} \quad \text{Equation 2}$$

(b) Evaluating weighs

Once the judgment matrices are constructed with the help of experts and using Equation 2, the next step is to determine the weight vectors of the requirements (macro and micro). Let us denote the current weights of the macro requirements by  $\{w_1, w_2, \dots, w_n\}$ , and the matrix of the ratios of all the weights by vector W. The  $a_{iq}$  elements of the judgment matrix estimate the ratio  $w_i/w_q$ , where W is the vector of the current weight of the macro requirements (which is our goal to determine). If the judgment matrix A is absolutely consistent of experts' judgment about the requirements, it can be noticed that  $A = W$ . In the case of such ideal case of total consistency, the principal eigenvalue ( $\lambda_{max}$ ) is equal to the n (where n the number of macro requirements identified). The relations between the weights and the experts judgment will be given by  $w_i/w_q = a_{iq}$  (for  $i, q=1, 2, \dots, n$ ) and shown in Equation 3.

$$W = [w_i/w_q] = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \dots & w_2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & \dots & w_n/w_n \end{bmatrix} \quad \text{Equation 3}$$

However, in reality, experts are not always consistent in their judgments due to lack of information or human error, and so on. If the matrix A is not absolutely consistent, it implies  $\lambda_{max} \neq n$ . In this case,  $\lambda_{max}$  can be determined using matrix algebra (Saaty 1980, 2001, 2008). The equation to determine the weight vectors for the macro and micro requirements is given in Equation 4.

$$AW = \lambda_{max}W \quad \text{Equation 4}$$

(c) *Checking consistencies*

Consistency is one of the main issues in pairwise comparison of AHP method. The matrix of judgment A can be said completely consistent if the following conditions are satisfied:

- ✓  $a_{iq} = w_i/w_q \quad i, q = 1, 2, \dots, n$
- ✓  $a_{iq} \cdot a_{qk} = a_{ik} \quad \forall i, q, k \rightarrow i \neq q \neq k$
- ✓  $\lambda_{max} = n$

In order to check the consistency of the judgment matrix A, Saaty (1980) proposed the consistency ratio (CR) as shown in Equation 5. RI is random index, which is the average value of CI for random matrices generated using the Saaty's scale. RI number is constant as a function of n. Forman (1990) obtained this constant for different dimensions of matrices up to n=7, see Table 7.2 below.

$$CR = \frac{\left(\frac{\lambda_{max} - n}{n - 1}\right)}{RI} \quad \text{Equation 5}$$

Other researchers also proposed RI values different from Forman's result and for larger matrix sizes (Alonso 2006). The general accepted threshold for CR is  $\leq 0.1$  (Saaty 1994).

Table 7.2: RI values for different matrix sizes (Forman 1990).

n	1	2	3	4	5	6	7
RI	0	0	0.52	0.89	1.11	1.25	1.35

If the CR is more than 10%, the judgment matrix should be readjusted in two ways. The first way is to ask experts again in order to reduce the inconsistency. The second way is following an iterative procedure (Saaty 1994). The iteration begins once the weight vector  $W$  has been obtained and CR is found to be  $> 10\%$ . In this procedure, the element  $a_{iq}$  of matrix  $A$  that causes the highest inconsistency will be substituted by  $w_i/w_q$  obtained from a previous iteration. Then, the weight vector  $W$  be recalculated until the CR is within the threshold.

To summarize, the main information needed from this step is the global importance level or weights of micro requirements (Equation 1). The weights of macro-requirements  $W(r_i)$  and micro-requirements  $W(r_j)$  can be obtained by following the AHP procedure described above.

## **7.2.2 Assess competitors' products and set targets**

As discussed previously, information solely based on customers are not sufficient to prioritize areas for SBCE processes. Some requirements might have less importance to customers but increase significantly competitiveness. Therefore, benchmarking competitors' products is taken as paramount in building SBCE IR to set improvement targets and prioritize contradictions.

To assess competitors performances three indicators are taken (Nieuwkuyk and Rogosch 1997): Present value ( $PV_j$ ), which shows the current performance of the product under investigation for a particular micro requirement  $j$ ; Target value ( $TV_j$ ), which shows the desired performance of the product for a particular micro requirement  $j$ , it will be set by considering the competitors performances and internal capability of the company to achieve the target performance; and Degree of difficulties ( $D_j$ ), which indicates the difficult of achieving the target values. It is assumed that, the higher is the degree of difficulties to achieve a target, the higher competitive advantages the company can get by improving the performance on the requirement (Yamashina, et al. 2002). If the difference between  $TV_j$  and  $PV_j$  is negligible, then  $D_j$  set to be zero. This indicates that the product is already optimized in satisfying the requirement. If the difference is considerable, then experts will assign scores for  $D_j$  using Equation 6.

$$D_j = \begin{cases} 0 & \text{already achieved} \\ 1 & \text{easily achievable} \\ 2 & \text{moderately difficult} \\ & \text{to achieve} \\ 3 & \text{difficult to achieve} \end{cases} \quad \text{Equation 6}$$

For example, looking the micro-requirement *easy installation* in Figure 7.3,  $PV_j$  is assigned as 'no' (i.e. the current design is difficult to install at customer sites) and the performances of the competitors' products ( $X$



and Y) are simple to install ('yes' for both). Thus, the designers think that improving the current design is important for competitiveness, and then they set  $TV_j$  as 'yes'. Moreover, designers of AHS acknowledge that improving the performance of the current design for the requirement is not a trivial design problem and set  $D_j = 3$ . Following similar logic, experts will assign  $D_j$  value for each micro-requirement.

### **7.2.3 Identify system contradictions**

As discussed before, contradictions lead to improvement areas. Experts can identify physical and technical contradictions by studying the micro requirements defined.

If two requirements are in contradiction (technical contradiction) a negative sign (-) will be assigned on the roof of the HOQ (see Figure 7.3). For example, taking the AHS case study, there is technical contradiction between requirements 'multi-zoning' and 'easy installation'. Customers are requesting to have a humidifier that can cover up to 12 zones (i.e. to distribute and spray water mists to 12 different areas in a building or in an industrial establishment). At the same time, customers want to install the humidifier in short period of time (easy installation). However, the current design serves only 6 zones and 12 zoning demands additional systems to be added into the product. Thus, more time is needed to install if a new product is designed for 12 zones.

If a requirement is in contradiction with itself (physical contradiction) a negative sign (-) will also be assigned on the roof of the HOQ (see Figure 7.3). Taking the AHS case study as an example, a requirement 'non-VDI Rack' is in contradiction with itself. The product should satisfy a European hygienic requirement called VDI6022. However, once the company is expanding its business to different countries and sectors, VDI6022 is not needed for some markets such as in some industrial applications (e.g. Tabaco industries, painting shops and so on) and the current design is expensive for these markets.

### **7.2.4 Identify causal contradictions**

In product system, contradictions identified in the previous step (7.2.3) are not all independent (Mizuyama and Ishida 2007). There are casual relationships between contradictions. That is, solutions proposed to overcome certain contradictions fully or partially alleviate other contradictions. If solutions feasible to solve a contradiction can overcome many other contradictions, then it would be efficient to take the root contradiction during prioritizing contradictions to pursue SBCE processes.

For example, consider the two contradictions in AHS case study, contradiction 1 ( $T_1$ : 'Multi-zone up to 12' Vs. 'Modulation range' and contradiction 2 ( $T_2$ ): 'Modulation range' Vs. 'Precision'.

$T_1$  implies that it is not possible to increase the zones (from the current 6 to the desired 12 zones) and at the same time increase the modulation range or the capacity of water flow (from the current range of [30-50 liters/hour or l/h] to the desired range of [1-50 l/h]), because a pump used in the current design has limitation to do so. On the other hand,  $T_2$  implies that it is not possible to increase the modulation range and at the same time achieve a desired level of precision in short time. Precision for this particular case is defined as the % of set point<sup>25</sup> reached. The desired precision level is reached through steps of increments. Thus, the contradiction  $T_2$  indicates that when the range of modulation is extended to lower values, it takes more time to arrive into the desired precision level. However, the engineers claimed that, if they design a new pump to overcome contradiction  $T_1$ , then contradiction  $T_2$  is automatically being solved too. Therefore,  $T_1$  has causal relationship with  $T_2$ .

However, as the number of contradictions in a product system grow, identifying such causal relationships are likely to be complicated. Moreover, there will not only be direct casual links but also indirect causal relationships (transitivity). Therefore, both direct and indirect relationships should be grasped and aggregated to identify causal relationships between contradictions. In this thesis, DEMATEL (Decision Making Trial and Evaluation Laboratory) is the method that is used to identify direct/indirect causal relationships between contradictions. It was developed by the Battelle memorial association of the Geneva research center (Fontela and Gabus 1974, 1978). The aim of DEMATEL is to directly compare the relationship between variables and use a matrix and causal diagram to express the casual relationships and influence level between variables in a complicated system. In recent years, it has been widely accepted and used in different fields in particular among Japanese, Korean and Taiwanese researchers and practitioners (Mizuyama and Ishida 2007; Hajime, et al. 2005; Lin and Wu 2008; Lee, et al. 2010). There are four steps in DEMATEL. The steps used in this thesis are explained as follows:

*a) Define measurement scale and establish a direct-relation matrix*

In order to define relationships between contradictions, experts will be asked to scale. The scale is used to identify how much of the problem in a contradiction ( $T_l$ ,  $l = 1,2,3 \dots m$ , where  $m$  is the number of contradictions identified) can be solved by overcoming another contradiction ( $T_k$ ,  $k = 1,2,3 \dots m$ ). The scale used in this thesis is between 0 and 1 (0 indicates that the two contradictions are not related at all, and 1 indicates there are completely related). Any value within 0 and 1 (0.2, 0.3...0.8, 0.9) can be used depending on the designers' assessment. Then, a direct relationship matrix  $X_{m \times m}$  can be defined as shown in Equation 7.

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<sup>25</sup> Set point in AHS is defined as the desired level of humidity level in a room.

$$X = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1m} \\ x_{21} & 0 & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & 0 \end{bmatrix} \quad \text{Equation 7}$$

b) Calculate normalized direct-relation matrix

To normalize the matrix  $X_{m \times m}$ , the biggest sum of the row vector can be used as coefficient. The normalizing coefficient  $\mu$  and the normalized matrix  $N_{m \times m}$  can be determined using Equation 8 and Equation 9.

$$\mu = \frac{1}{\max_{1 \leq k \leq m} (\sum_{l=1}^m x_{lk})} \quad \text{Equation 8}$$

$$N = \mu X \quad \text{Equation 9}$$

c) Direct/ indirect-relation matrix

The direct/ indirect-relation matrix shows the total relations between contradictions. For a contradiction, the matrix  $F_{m \times m}$  that is determined using Equation 10 shows the total direct and indirect relations it has with other contradictions. As discussed before, contradictions might be solved by resolving other contradictions directly or indirectly.

$$F = N(I - N)^{-1}, \text{ where } I \text{ is an identity matrix of } m \times m \quad \text{Equation 10}$$

Now, set the elements  $t_{lk}$  of the total matrix  $F$ . The columns' and rows' sums of the total matrix  $F$  can be determined using Equation 11 and Equation 12 respectively.  $D_l$  represents the total row sum of contradiction  $T_l$ , and indicates its total impact to other contradictions  $T_k$ . That is, the total contributions of design solutions proposed to overcome contradiction  $T_l$  for other contradictions.  $R_l$  represents the total column sum of contradiction  $T_l$ , and indicates the total impacts of other contradictions on  $T_l$ . That is, the total contributions of design solutions generated to resolve other contradictions on  $T_l$ .

$$D_l = \sum_{k=1}^m t_{lk} \text{ (where } l = 1, 2, \dots, m) \quad \text{Equation 11}$$

$$R_l = \sum_{l=1}^m t_{lk} \text{ (where } k = 1, 2, \dots, m) \quad \text{Equation 12}$$

d) Draw out causal diagram

To visually depict complicated relationships of contradictions, causal diagram will be useful. Therefore, using Equation 11 and Equation 12, define  $(D_l + R_l)$  for  $T_l$  as the prominence which shows the overall level of  $T_l$  impact to and impacted by other contradictions. Then, define  $(D_l - R_l)$  as the relationship, which shows the causal level of the contradiction. If this value is positive, then the contradiction is the cause, and solutions proposed to overcome it will also be solutions to solve other contradictions. If this value is negative, the contradiction is an effect, and solutions proposed to overcome other contradictions will solve the inherent contradiction in  $T_l$ . Furthermore, use  $(D_l + R_l)$  as the transverse axis and  $(D_l - R_l)$  as the longitudinal axis to construct causal diagram. It helps experts to easily identify those contradictions which are the root causes of other contradictions.

### **7.2.5 Derive rules to prioritize contradictions**

At this step rules to prioritize contradictions for SBCE implementation is derived. From the previous step 4 (section 7.2.4), contradictions which have strong causal relationships can be identified. But, there are also contradictions which do not exhibit significant causal relationships. Thus, the two should be treated separately in deriving the rule. In this thesis, contradictions which do not have strong causal relationships are called independent contradictions and those which exhibit strong causal relationship are called dependent contradictions. The prioritization schemes for the two are explained as follows:

#### *a) Prioritizing independent contradictions*

Independent contradictions can be prioritized using the information in step 1 and 2 (sections 7.2.1 and 7.2.2). Each contradiction has two information sources from its contradictory requirements: global weight  $GW(r_j)$  and degree of difficulties  $D_j$ . Thus, first these requirements can be prioritized and ranked. The priorities ( $P_j$ ) and ranks ( $Rank_j$ ) of micro-requirements can be determined using Equation 13 and Equation 14 respectively. Note however that  $Rank_j$  is determined taking micro-requirements with the same macro-requirement category. Moreover, the convention on the ranking in Equation 13 is in decreasing order except when it is zero (i.e.  $1 > 2 > 3 \dots > 0$ ). Taking the example from Figure 7.3, the  $P_j$  value for micro-requirements ‘non-VDI Rack’ is 0.098, and among all the cost category this requirement is ranked as 2 ( $Rank_j = 2$ ).

$$P_j = GW(r_j) * D_j \quad \text{Equation 13}$$

$$Rank_j = \begin{cases} 1, 2, \dots, n, & \text{if } P_j \neq 0 \\ 0, & \text{if } P_j = 0 \end{cases} \quad \text{Equation 14}$$

Now, using the  $Rank_j$  values, independent contradictions can also be ranked. Two cases are possible: domination (case 1) and tie (case 2). In the former case, a dominating contradiction has higher rankings in

both of it contradictory requirements than a dominated one. But, in the case of tie a contradiction neither dominates nor dominated by another contradiction in the ranking of its contradictory requirements. For example, let's take five hypothetical contradictions  $T_1, T_2, T_3, T_4$  and  $T_5$ , with the rankings of the corresponding contradictory requirements shown in Figure 7.4. In this example, there are four scenarios: (a/c)  $T_1$  dominates  $T_2$  and  $T_4$ , (b)  $T_1$  is in tie with  $T_3$ , (d)  $T_5$  dominates  $T_1$ . Therefore, for SBCE implementation dominating contradictions will have higher priorities if designers are presented to choose among contradictions. But, in case of tie, experts' judgments should be used taking other criteria such as resources and/or capabilities available to pursue SBCE to overcome contradictions.

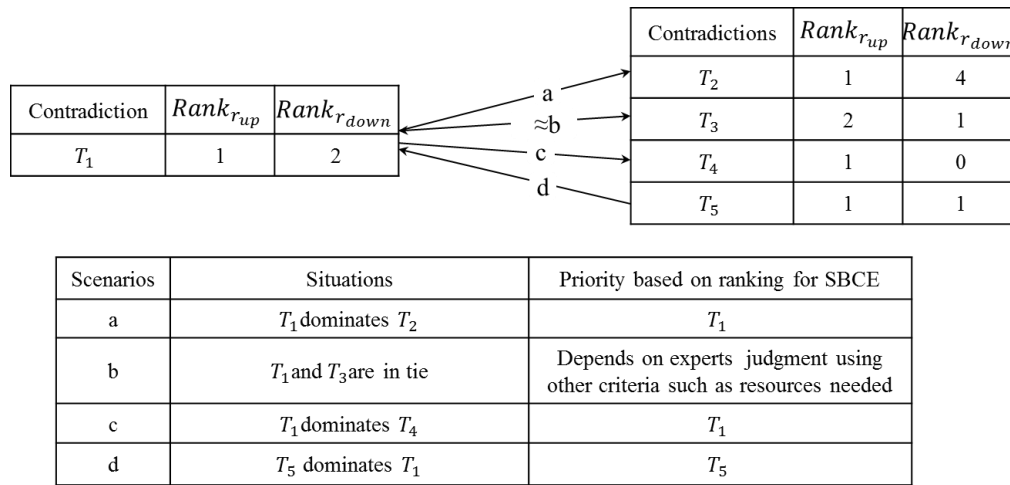


Figure 7.4: Examples of priority rules of independent contradictions for SBCE implementation<sup>26</sup>.

b) *Prioritizing dependent contradictions*

In case of dependent contradictions (let's call this a third case), prioritizing based on the ranking method introduced above is not efficient. Let's take the scenarios presented in Figure 7.4. Suppose in step 4 (section 7.2.4) it is found that  $T_1$  is the root contradiction for  $T_3$  and  $T_5$ , i.e. design solutions proposed for  $T_1$  will also overcome  $T_3$  and  $T_5$ . Thus, it is efficient to start SBCE process to solve contradiction  $T_1$  even if it is dominated by  $T_5$  and is in tie with  $T_3$ . Therefore, more innovation can be achieved by focusing on the root contradictions with less effort.

In summary, in order to prioritize between contradictions three rules are derived for the three cases introduced: *case 1*, dominating contradiction; *case 2*, tie contradictions and *case 3*, dependent contradictions. The rules to follow to select a contradiction over another for SBCE are shown in Equation 15.

<sup>26</sup>  $Rank_{r_{up}}$  and  $Rank_{r_{down}}$  are the rankings of the contradictory requirements (where:  $up, down \in j$ ).

$$\text{Select} \sim \begin{cases} \text{dominating contradiction in case 1} \\ \text{based on experts' judgment in case 2} \\ \text{root cause contradiction in case 3} \end{cases} \quad \text{Equation 15}$$

### **7.2.6 Map contradictions to design factors**

Once contradictions are prioritized, designers at this step map selected contradictions to design factors. This step is aimed to identify what design factors (e.g. material type, dimensions, number of components used) that can possibly be changed in the current design to overcome the contradictions. Once mapping is finished, SBCE processes starts to explore, communicate, test and converge to solutions proposed to overcome the contradictions. Thus, the selected contradictions with the design factors will be input to SBCE.

## **7.3 Validation of SBCE IR methodology**

In order to validate the applicability of the SBCE IR methodology three validations are conducted. First, a case study on Adiabatic Humidification System (AHS) has been conducted. The case study is aimed at applying the steps of the methodology in real case. The necessary data are collected to demonstrate the steps. Section 7.3.1 is dedicated for the discussion of this case study.

The second phase of the validation is concerned with experimentation of an SBCE process on one of the subsystem of AHS. Using the SBCE IR developed for AHS, designers and managers have selected a subsystem called Rack to experiment SBCE process to overcome a contradiction and improve the current design. Throughout the process concepts are generated by the AHS experts that can improve the Rack design to overcome the contradiction. Moreover, the concepts are tested and merged to maximize the value of the new Rack proposed. The new Rack design is expected to have significant cost advantages and the company plans to launch it soon. Section 7.3.2 is dedicated to introduce the SBCE process on Rack subsystem.

Finally, open questionnaire is prepared to assess the pros and cons of the SBCE IR. Four experts in Carel Industries who are involved in AHS design and development were asked to give feedback to assess SBCE IR. Section 7.3.3 is dedicated to introduce the questionnaire and report the assessment.

### **7.3.1 Case study on Adiabatic Humidification System (AHS)**

The SBCE IR for AHS is built with close interactions with designers and managers at the case company. The AHS system is a product that is used primarily for industrial applications (such as hospitals, residential buildings, textile factories, paint shops in car industries, and so on). The main function of the system is to control the temperature and humidity levels of a room or a working environment. The product is the state of

the art among other humidification systems in terms of energy savings. The working principle is based on spraying atomized water mists to air with at high pressure (around 70 bars) whenever the temperature and humidification levels are not desirable. That is where it gets its name; adiabatic refers to a very high pressure used to spray atomized water. The basic subsystems are three Cabinet (C), Drop Separator (DS), and Rack (R) as shown in Figure 7.5.

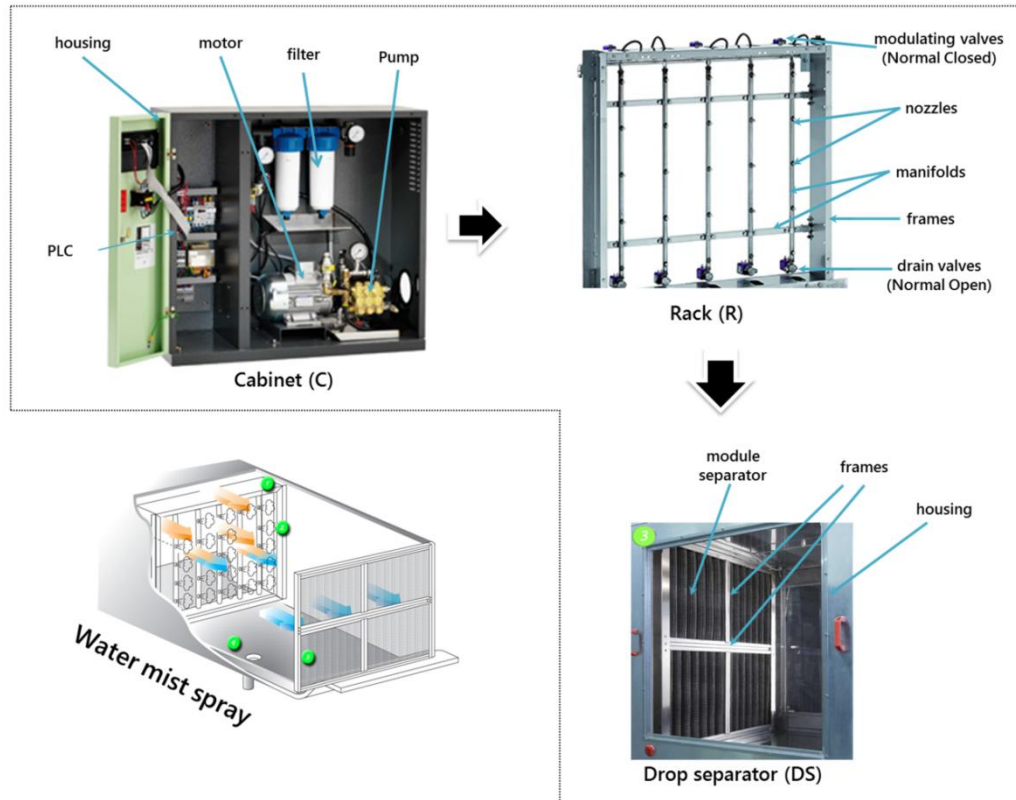


Figure 7.5: AHS sub-systems and components.

Inside the Cabinet subsystem there are components used to control the product (PLC, programmable logic control), water filtering (filters), pumping water (pump), and rotate the pump (motor). Inside the Drop Separator, components are included that are used to achieve a high purity level of the water content (module separator), support the separator (frames) and protect the separator from the environment (housing). The Rack is the sub-system used to spray water mists to an environment, and its includes components such as modulating and drain valves, nozzles for spraying, frames for support, and manifolds to carry nozzles and transport water. The sub-systems are integrating with piping system and fittings.

The product has been in the market for the last 10 years, and is among the leading products in the market. The company sells the product to all over the world such as EU, USA, South America, Asia, Middle East and

Africa. The sales volume of the product is medium and the average unit price of the product is about 8,700 €. Moreover, the company controls the lifecycle of the product and profit margins are also gained from maintenance and consulting services.

The AHS case study has been conducted for six months to collect all the data to build the SBCE IR. The steps of the methodology also evolved throughout the study period. Two highly experienced designers of the system with an experience of 12 and 24 years of experience were involved throughout the study.

The data presented in this thesis are only those which are necessary to validate the SBCE IR. Thus, the details discussions of some of the technical information are not exposed for privacy reasons. The case for each of the steps of the methodology is presented in following subsections.

### **7.3.1.1 *Identify customer requirements and assign importance***

The first step is to capture customer value information and assign importance for each. The experts conducted extensive study using phone calls and visiting customers to identify real customer requirements. Moreover, internal discussions with upper management and marketing were held to identify new and emerging requirements that customers are not able to identify.

The classifications of the requirements are grouped under macro and micro requirements. Five macro requirements are identified: (1) Technical performance (P), which is related to the technical quality characteristics that the product should satisfy; (2) Usability (U), which is related to the product's simplicity during installation and use; (3) Application (A), which is related to the flexibility of the system to be used in different applications (paint shop, data centers, hospitals, etc.); (4) Costs (C), aimed to minimize the cost of the system; (5) Maintenance (M), is to achieve easy repair of components and reduce time between check-ups.

For each of the five macro-requirements, specific micro-requirements are defined. For P, U, A, C, and M there are 11, 4, 5, 5, and 1 micro- requirements identified respectively. For example, for usability (U), the micro requirements are: U1 (wide option range), to have a user interface in different languages and make the product to operate wider operations during user-product interactions, U2 (Integration to AHU); to enable the product to fit into customers sites; U3 (easy installation); to reduce the time it takes to install the product at the customers sites; U4 (Friendly user interface); to simplify the user interface very easy to be used by users (the product is programmable, thus the user need to frequently interact with it to control the temperature and humidity level of a room).

In order to assign importance to the customer needs, the macro and micro-requirements are assigned judgment matrices separately based the scaling scheme listed on Table 7.1 and using Equation 2. Treating



them separately simplifies the judgment and importance assignment process. Designers made pairwise comparison between each macro-requirement, as shown in Table 7.3. Moreover, judgment matrices and weight assignments are given for each group of micro-requirements under their respective macro classifications. Table 7.4 shows the judgment matrix for the identified micro-requirements of usability (U). Similarly, judgment matrices are built for all the other micro-requirements.

Table 7.3: Judgment matrix A for macro-requirements.

	P	U	A	C	M
Performance (P)	1	5	1	3	9
Usability (U)	1/5	1	1/7	1/5	3
Application (A)	1	7	1	1	6
Costs (C)	1/3	5	1	1	8
Maintenance (M)	1/9	1/3	1/6	1/8	1

Table 7.4: Judgment matrix A for usability (U) micro-requirements.

	U1	U2	U3	U4
Wide option range (U1)	1	2	1	3
Integration on AHU (U2)	1/2	1	1/2	2
Easy installation (U3)	1	2	1	3
Friendly user interface (U4)	1/3	1/2	1/3	1

The next step is to determine weight vectors of macro and micro-requirements,  $W(r_i)$  and  $W(r_j)$ . The vectors are iteratively obtained using Equation 4. Consistence of the experts in defining a judgment matrix can also be checked using Equation 5. If the CR > 10%, the steps in Equation 4 and Equation 5 will be done until an acceptable level of consistency is achieved. Table 7.5 shows the procedure used in ‘MATLAB 7.0’ to automate the determination of importance and checking consistency for a given judgment matrix.

The values of  $W(r_i)$  and  $W(r_j)$  for AHS system is shown in Figure 7.6. The result shows that technical performance, application and costs macro-requirements have the highest importance for customers with weights 37%, 29%, and 24% respectively. Moreover, the global weight of the micro- requirements  $GW(r_j)$  is calculated using Equation 1. Figure 7.6 shows  $GW(r_j)$  value for each micro-requirement. For example, ‘non-VDI Rack’ requirement has a global importance of 10% from customers’ perspective.

		Competitors' performances for each $\gamma_j$								AHS performances for each $\gamma_j$ in current design																																										
				Competitor 1	Competitor 2	Competitor 3	Competitor 4	$PV_j$	$TV_j$	$D_j$	$\beta_j$	$Rank_j$	j	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	U1	U2	U3	U4	A1	A2	A3	A4	A5	C1	C2	C3	C4	C5	M1													
Macro-requirements (G)	Technical performances (P)	37	P1	Temperature control	6	2	high	high	high	low	high	higher	2	0.045	5	P1																																				
			P2	Multi-zone up to 12	12	5	4	1	1	1	6	12	2	0.091	1	P2			(-)			(-)																														
			P3	Motor efficiency	2	1	NA	NA	NA	IE2	N	IE2	3	0.023	7	P3																																				
			P4	Modulation range	11	4	14 to 100%	33 to 100%	25 to 100%	20 to 100%	12 to 100%	3 to 100%	2	0.083	3	P4				(-)	(-)				(-)																											
			P5	Precision	6	2	Y	Y	Y	Y	Y	Y	ok	0.000	8	P5						(-)																														
			P6	(Lsh) [e]	7	3	Y	Y	Y	Y	Y	Y	ok	0.000	8	P6																																				
			P7	IP20	1	0	IP30	IP31	NA	IP54	IP20	IP20	0	0.000	8	P7																																				
			P8	Humidity control precision	9	3	4%	10%	5%	NA	2%	≤2%	2	0.068	4	P8																																				
			P9	CE UL	27	10	Y	Y	Y	Y	Y	ok	0	0.000	8	P9																																				
			P10	Absorption efficiency	9	3	low	low	NA	high	high	higher	1	0.034	6	P10																																				
			P11	Capacity	10	4	21 to 1080l/h	20 to 1000l/h	180 to 420l/h	100 to 800l/h	100 to 600l/h	50 to 1000l/h	2	0.075	2	P11																																				
Macro-requirements (G)	Usability (U)	6	U1	Wide option range	35	2	N	NA	N	Y	N	ok	0.000	2	U1																																					
			U2	Integration on AHU	19	1	NA	Y	Y	N	Y	ok	0	0.000	2	U2																																				
			U3	Easy Installation	35	2	Y	N	Y	Y	N	improve	3	0.065	1	U3																																				
			U4	Friendly user interface	11	1	Y	Y	Y	Y	Y	ok	0	0.000	2	U4																																				
Macro-requirements (G)	Application (A)	29	A1	Silicone free pump	4	1	NA	Y	NA	Y	Y	ok	0	0.000	2	A1																																				
			A2	RO system	21	6	Y	Y	N	Y	Y	ok	0	0.000	3	A2																																				
			A3	Backup features	4	1	N	N	N	N	Y	Y	2	0.023	2	A3																																				
			A4	Hygienic	31	9	N	N	N	N	N	Y	3	0.273	1	A4																																				
			A5	Automatic washing cycles	40	12	Y	Y	N	NA	Y	ok	0	0.000	3	A5																																				
Macro-requirements (G)	Costs (C)	24	C1	Non added value rack component	27	6	NA	NA	NA	NA	high	15% reduction	1	0.063	4	C1																																				
			C2	Drop separator cost	3	1	NA	NA	NA	NA	high	reduce	3	0.021	6	C2																																				
			C3	Pumping unit cost	8	2	NA	NA	NA	NA	high	20% reduction	3	0.056	5	C3																																				
			C4	Valves installation	2	5	NA	NA	NA	NA	high	20% reduction	2	0.094	3	C4																																				
			C5	Non-VDI6022 rack	42	10	N	N	N	N	N	Y	1	0.098	2	C5																																				
Macro-requirements (G)	M(3 %)	3	M1	Maintenance	100	3	500 to 2000 hrs	2000 hrs	500 hrs	NA	2000 hrs	1000hrs	3	0.099	1	M1																																				

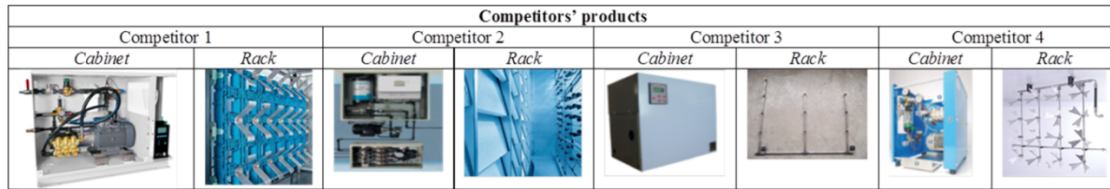


Figure 7.6: Results from steps 1, 2, 3 of SBCE IR (Note: Y=yes, N=no, NA= data not available, (-) contradiction, ok = keep the current performance of the AHS design).

Table 7.5: MATLAB procedure to determine weights for macro and micro-requirements and to check CR.

a.	>> insert a square judgment matrix $\rightarrow [A_{n \times n}]$	// see Equation 2
b.	>> calculate the eigenvalues (V) and vectors (D) of a square judgment matrix $[A_{n \times n}] \rightarrow [V, D] = \text{eig}(A)$	
c.	>> set normalization coefficient $x \rightarrow x = \text{sum}(V(:,1))$	// see Equation 4
d.	>> calculate the weight vector $w \rightarrow w = V(:,1)/x$	// see Equation 4
e.	>> calculate $m_i \rightarrow m_i = (D(1,1)-n)/(n-1)$	// n is the dimension of matrix $[A_{n \times n}]$
f.	>> calculate consistency ration (CR) $\rightarrow CR = m_i/RI$	// RI is random index, see Equation 5
g.	>> [If $CR > 0.1$ ] >> determine matrix B $\rightarrow B(i, j) = A(i, j) * w(j)/w(i)$	
h.	>> identify the maximum element $\{b_{ij}\}$ of matrix B and substitute the $a_{ij}$ with $w(i)/w(j) \rightarrow A(i, j) = w(i)/w(j)$	
i.	>> repeat steps 'a-h' until $CR \leq 0.1$	

### 7.3.1.2 Assess competitors' products and set targets

Four competitors' products are selected. To set targets for improvement and to determine  $D_j$  values (Equation 6), the performances of competitors' designs are evaluated by the AHS experts for each micro-requirement (see Figure 7.6). The indicators to measure the performances of micro-requirements are different. Some are quantitative and others are qualitative depending on the types of requirements. For example, the indicator used for 'multi-zone (P2)' is the number of zones to serve. The number of zones that the competitors' products serve ranges from 1 to 4. The current AHS design serves 6 ( $PV_{P2} = 6$ ). However, customers of AHS are requiring the zones to be 12 ( $TV_{P2} = 12$ ). Using Equation 6, the designers set the  $D_{P2}$  as 2 since it is moderately difficult to change the current design technology. On the other hand, the measure used for 'non-VDI6022 Rack (C5)' requirement is qualitative. That is, yes (Y) if a design is also built for non-VDI6022 clients or no (N) if otherwise. The competitors' products do not satisfy this emerging requirement. Neither does the case product ( $PV_{C5} = N$ ). But since there is emerging markets looking for a cheaper non-VDI Rack version, AHS designers set the target as 'yes' ( $TV_{C5} = Y$ ). Moreover, since modifying the current AHS system for non-VDI clients is easily achievable, the designers set the degree of difficulties  $D_{C5}$  as 1. All the  $D_j$  values are shown in Figure 7.6.

### 7.3.1.3 Identify system contradictions

In total, 22 technical and 1 physical contradictions are identified and marked (-) signs in Figure 7.6. In Table 7.6, the contradictions are designated. As seen from the result, six of the contradictions (T1 to T6) are between technical requirements, and the rest are either between technical requirements and business related requirements (Usability, Application, Costs) or between businesses related requirements. This shows the

current AHS design is highly optimized for technical performances but need significant innovation to maximize business related performances. And, each contradiction is a potential input to SBCE process to uncover solutions and converge to high value design to overcome contradictions. Refer to section 7.2.3 for the detail explanation on an example from technical contradiction T7 (‘multi-zoning’ vs. ‘easy installation’) and example of physical contradiction T21 (‘non-VDI Rack’ vs. ‘non-VDI Rack’).

Table 7.6: Contradictions and the respective contradictory requirements.

Contradictions	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
$r_{up}$	P2	P4	P4	P5	P2	P4	P2	U3	U3	A4
$r_{down}$	P4	P5	P6	P6	P8	P10	U3	C1	C2	C2

T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23
P3	P10	P11	A1	A3	P4	P6	P8	A4	C1	C5	A1	A4
C3	C3	C3	C3	C3	C4	C4	C4	C4	C4	C5	M1	M1

### 7.3.1.4 Identify casual contradictions

Using Equation 7 of DEMATEL, designers scale the direct relationships between contradictions from a scale of 0 to 1. A direct-relationship matrix X is constructed as shown in Table 7.7. The matrix shows if design solutions proposed for a contradiction overcome other contradictions. For example, the relationship between T2 and T1 is scaled as 1 ( $x_{21} = 1$ ), implying that overcoming T2 completely resolve T1 (see section 7.2.4 for detail discussion on this example).

However, the relations between contradictions are not only direct but also there are indirect relations. For example, solving contradiction T2 can solve the inherent contradiction in T1 ( $x_{21} = 1$ ). Moreover, solving T1 also solves the inherent contradiction in T6 ( $x_{16} = 1$ ). From transitivity, it means that solving T2 solves indirectly contradiction T6. Thus, the total direct and indirect or total relationship matrix F will explain such relations.

Using Equation 9, F is determined as shown in Table 7.8 (the normalizing coefficient  $\mu$  is calculated as 1/5.8 using Equation 8). Taking T2 as an example from the matrix F, it can be seen that its total impact on other contradictions can be read from the matrix. Solving contradiction T2 means that there are relative chances of 0.28, 0.08, 0.08, 0.16, 0.23, and 0.22 of solving T1, T2, T3, T4, T5 and T6 respectively.

Now, the column (D) and row (R) sums of matrix  $F$  can be calculated using Equation 11 and Equation 12 respectively. D indicates the total impact of a contradiction over others. R indicates the influences of others on a contradiction. For example,  $D(T2) = 0.06 + 0.08 + \dots + 0 = 1.19$ , and  $R(T2) = 0.28 + 0.08 + 0.08 + 0.16 + 0.23 + 0.22 + 0.00 + \dots + 0.00 = 1.05$ . The D and R values of each contradiction are shown in Table 7.9.

Table 7.7: Direct-relationship matrix  $X$  of contradictions<sup>27</sup>.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T12	T13	T16	T17	T18	T19	T20	T21
T1	0	0	0.2	0.4	0.3	1	0	0	0	0	0	0	0	0	0	0	0
T2	1	0	0.2	0.4	1	0.8	0	0	0	0	0	0	0	0	0	0	0
T3	1	0.5	0	0.5	0.5	1	0	0	0	0	0	0	0	0	0	0	0
T4	0.8	0.5	0.5	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0
T5	0.5	0.5	0.4	0.8	0	0.2	0	0	0	0	0	0	0	0	0	0	0
T6	1	1	0.2	0.6	0.5	0	0	0	0	0	0	0	0	0	0	0	0
T7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T8	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0
T9	0	0	0	0	0	0	0.8	0.6	0	0	0	0	0	0	0	0	0
T12	0.3	0.4	0.2	0.4	0.2	0.6	0	0	0	0	0	0	0	0	0	0	0
T13	0.4	0.2	0.4	0.2	0.4	0.2	0	0	0	0	0	0	0	0	0	0	0
T16	0.8	0.4	0.2	0	0	0	0	0	0.2	0	0	0	0	0.4	0	0	0
T17	0	0	0.4	0.2	0	0	0	0.5	0	0	0.2	0.4	0	0.2	0	0.2	0
T18	0	0.2	0.2	0	0	0.4	0	0	0	0	0.4	0.2	0	0	0	0	0
T19	0	0	0	0	0	0	0	0	0	0	0.2	0.2	0	0	0.6	0.8	0
T20	0	0	0	0	0	0	0	0	0	0	0.6	0.2	0	0.8	0	0	0
T21	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0

Table 7.8: Normalized direct/indirect or total relation matrix  $F$  of contradictions.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T12	T13	T16	T17	T18	T19	T20	T21
T1	<b>0.08</b>	<b>0.06</b>	<b>0.06</b>	<b>0.12</b>	<b>0.09</b>	<b>0.21</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T2	<b>0.28</b>	<b>0.08</b>	<b>0.08</b>	<b>0.16</b>	<b>0.23</b>	<b>0.22</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3	<b>0.29</b>	<b>0.16</b>	<b>0.05</b>	<b>0.17</b>	<b>0.16</b>	<b>0.27</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T4	<b>0.21</b>	<b>0.12</b>	<b>0.11</b>	<b>0.05</b>	<b>0.05</b>	<b>0.11</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T5	<b>0.18</b>	<b>0.13</b>	<b>0.10</b>	<b>0.19</b>	<b>0.05</b>	<b>0.11</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T6	<b>0.28</b>	<b>0.23</b>	<b>0.08</b>	<b>0.18</b>	<b>0.16</b>	<b>0.11</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T8	0.00	0.00	0.00	0.00	0.00	0.00	<b>0.14</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T9	0.00	0.00	0.00	0.00	0.00	0.00	<b>0.15</b>	<b>0.10</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T12	<b>0.13</b>	<b>0.12</b>	<b>0.06</b>	<b>0.12</b>	<b>0.08</b>	<b>0.16</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T13	<b>0.13</b>	<b>0.07</b>	<b>0.09</b>	<b>0.08</b>	<b>0.10</b>	<b>0.09</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T16	<b>0.19</b>	<b>0.10</b>	<b>0.06</b>	<b>0.04</b>	<b>0.04</b>	<b>0.07</b>	0.00	0.00	0.00	<b>0.03</b>	0.00	0.00	0.00	<b>0.07</b>	0.00	0.00	0.00
T17	<b>0.05</b>	<b>0.03</b>	<b>0.09</b>	<b>0.05</b>	<b>0.02</b>	<b>0.03</b>	<b>0.01</b>	<b>0.09</b>	0.00	0.00	<b>0.03</b>	<b>0.08</b>	0.00	<b>0.04</b>	0.00	<b>0.04</b>	0.00
T18	<b>0.05</b>	<b>0.07</b>	<b>0.05</b>	<b>0.03</b>	<b>0.03</b>	<b>0.10</b>	0.00	0.00	0.00	0.00	0.00	<b>0.07</b>	<b>0.03</b>	<b>0.01</b>	0.00	0.00	0.00
T19	<b>0.01</b>	<b>0.01</b>	<b>0.01</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	<b>0.05</b>	<b>0.04</b>	0.00	<b>0.03</b>	<b>0.11</b>	<b>0.14</b>
T20	<b>0.02</b>	<b>0.01</b>	<b>0.01</b>	0.01	0.00	<b>0.01</b>	0.00	0.00	0.00	0.00	0.00	<b>0.11</b>	<b>0.04</b>	<b>0.01</b>	<b>0.14</b>	<b>0.02</b>	<b>0.02</b>
T21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	<b>0.01</b>	<b>0.01</b>	0.00	<b>0.14</b>	<b>0.01</b>	<b>0.02</b>

<sup>27</sup> Note that T10, 11, 14, 15, 22, and 23 are not shown since they do not have relationship with any other contradictions.

Table 7.9: Causal influence level of contradictions.

<b>T</b>	<b>D</b>	<b>R</b>	<b>D + R</b>	<b>D - R</b>
T1	0.63	1.91	2.54	-1.28
T2	1.05	1.19	2.24	-0.14
T3	1.10	0.86	1.96	0.24
T4	0.65	1.19	1.85	-0.54
T5	0.76	1.01	1.77	-0.25
T6	1.03	1.49	2.52	-0.46
T7	0.00	0.30	0.30	-0.30
T8	0.14	0.20	0.34	-0.06
T9	0.26	0.00	0.26	0.26
T12	0.68	0.05	0.73	0.64
T13	0.58	0.04	0.61	0.54
T16	0.60	0.32	0.92	0.27
T17	0.56	0.13	0.69	0.44
T18	0.45	0.13	0.58	0.32
T19	0.42	0.33	0.75	0.09
T20	0.41	0.18	0.59	0.24
T21	0.20	0.18	0.38	0.01
		<b>Average</b>	<b>1.12</b>	<b>0</b>

The sum  $D + R$  shows the total connections of a contradiction with other contradictions in the AHS system. The higher this value, the higher interaction a contradiction has with others. The difference  $D - R$  shows the cause or the effect behavior of a contradiction. A higher negative this value for a contradiction implies an effect and a lower negative value shows a cause. For example, looking the  $D - R$  values of T1 (-1.28) and T2 (-0.14), T2 is a cause and overcoming it provides solutions for many other contradictions, and T1 is an effect and solutions proposed for other contradictions eventually overcome the inherent contradiction in T1.

Taking the averages of  $D + R = 1.12$  and  $D - R = 0$  as vertical and horizontal axes respectively, the causal diagram can be drawn as shown Figure 7.7. As it is shown in the figure, except the contradictions T1, T2, T3,

T4, T5, and T6, all the other contradictions (T7 to T21) have prominence values (D + R) below the average (1.12). This result implies that, contradictions from T7 to T21 do not have considerable interrelationships between with other contradictions in the system. However, contradictions T1 to T6 as expected<sup>28</sup> have considerable interrelationship. Moreover, drawing all the relationships between the contradictions is too complex, and it will be difficult to visualize important relationships.

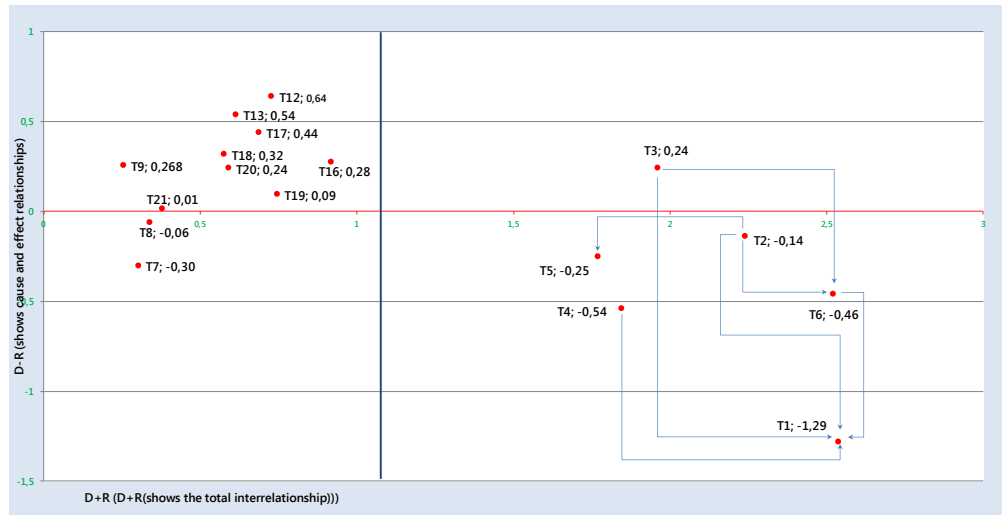


Figure 7.7: DEMTEL causal relations between contradictions in AHS.

To sort out significant causal relationships, a threshold of 0.2 in F matrix is considered (Lee, et al. 2010). That is, to cut all the relationships which have the normalized direct/indirect relations below 0.2 and  $F_{Cut=0.2}$  matrix is constructed as shown in Table 7.10.

Table 7.10: Normalized direct/indirect or total relation matrix  $F_{cut = 20\%}$  of contradictions.

	T1	T2	T3	T4	T5	T6
T1						0.21
T2	0.28				0.23	0.22
T3	0.29					0.27
T4	0.21					
T5						
T6	0.28	0.23				

<sup>28</sup> Contradictions T1 to T6 are formed from technical performance requirements, and these requirements are highly related to each other.

### 7.3.1.5 Derive rules to select contradictions to start SBCE processes

From previous step 4, it has been possible to identify the causal relationships between contradictions and separate dependent and independent ones. From Table 7.10, contradictions T1 to T6 are dependent and the rest T7 to T23 are independent contradictions. Referring the discussions in section 7.2.5, the dependent contradictions are be prioritized taking the root cause contradictions and independent ones are prioritized using the rankings of the corresponding contradictory requirements.

➤ *Prioritizing dependent contradictions*

Using the  $F_{Cut=0.2}$  shown in Table 7.10 and the causal diagram in Figure 7.7, the causal relationships between of T1 to T6 can be shown as in Figure 7.8. The rule to select between dependent contradictions is given in Equation 15. For example, contradiction T2 is the root cause of T5, T6 and T1, therefore, designers should give priority for T2 to be overcome. Although T2 is in tie in ranking with T5 and dominated by T1 and T6, starting SBCE process for T2 will provide solutions for T2, T5, T6 and T1 simultaneously. Therefore, more innovations can be obtained efficiently.

Similarly, T3 is the root contradiction for T6 and T1. If designers have to select a contradiction for SBCE to pursue, T3 should be given high priority although dominated by both its effect contradictions (T6 and T1).

T4 on the other hand, is a root contradiction for T1 directly and for T6 indirectly. If designers have to choose between T4, T1 and T6, then T4 is given high priority irrespective of the ranking of the contradictory requirements, which are dominated by both the ranking of the contradictors requirements of contradictions T1 and T6.

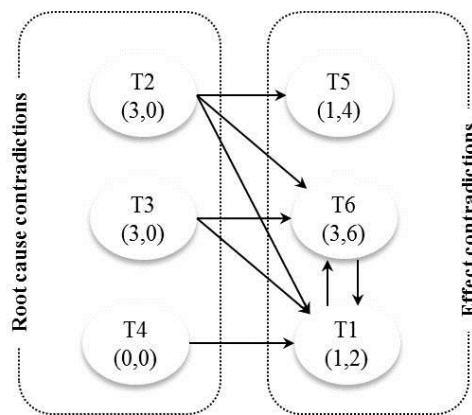


Figure 7.8: Causal relations of dependent contradictions.<sup>29</sup>

<sup>29</sup> Note that: the ranking of the contradictory requirement are shown in the brackets.



➤ *Prioritizing independent contradictions*

For independent contradictions, prioritizing is based on the ranking of the contradictory micro-requirements ( $Rank_j$ ) calculated using Equation 14. The ranks of each micro-requirement are shown in Figure 7.6 above. Moreover, Figure 7.9 shows the independent contradiction and the rankings of the requirements in conflict. Looking at Figure 7.9, it is possible to identify dominating and tie contradictions in which prioritizing rules listed in Equation 15 can be used to select contradictions for further SBCE implementations.

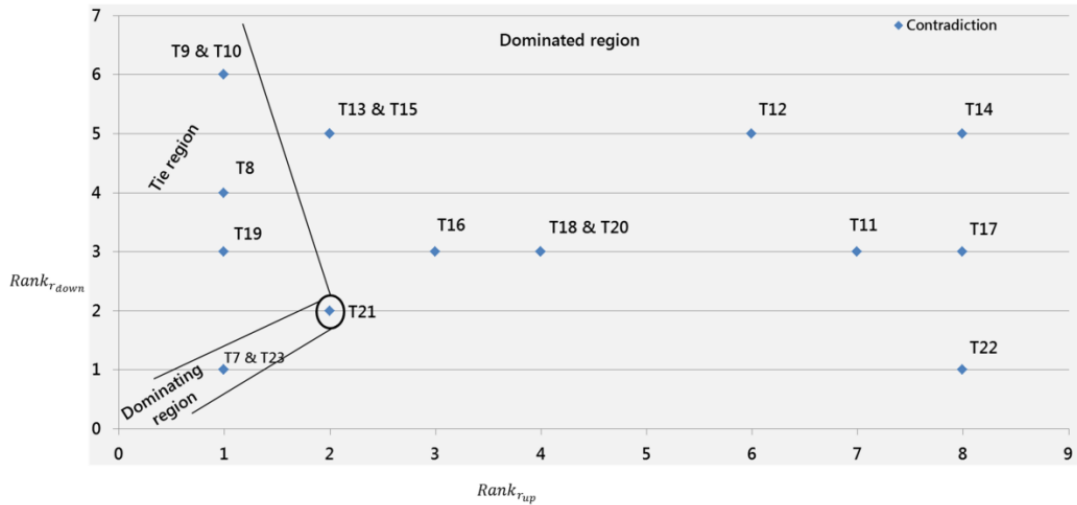


Figure 7.9: Independent contradictions and the rankings of corresponding contradictory requirements<sup>30</sup>.

Taking T21 as example from Figure 7.9, it is dominated by T7 and 23, is in tie with T8, 9, 8 and 10, and it dominates all the rest of independent contradictions. If designers are confronted to choose between T21 and its dominating contradiction, using the rules listed in Equation 15, efforts should be made to overcome T7 and 23 before T21. On the other hand, T21 should be selected for SBCE implementation before any contradictions that it dominates.

Moreover, as it is stated in Equation 15, experts have to impose other criteria other than customer importance and competitiveness to select between T21 and contradictions that are in tie (T8, 9, 8 and 10). These criteria could be resources and capabilities available in product development that are necessary to overcome the contradictions. Moreover, since the company is sourcing most of its components from suppliers, the capabilities are not limited to internal ones but also to the external suppliers. If suppliers' technologies are not ready to make innovative solutions to overcome certain contradictions, experts should evaluate these

<sup>30</sup> According to the convention introduced in section 7.2.5, the rankings are decreasingly ordered except for zero. T22, T17 and T14 have the  $Rank_{r_{up}} = 0$ , and these contradictions are shifted to  $Rank_{r_{up}} = 8$  in Figure 7.9.

kinds of aspects into consideration during prioritizing contradictions. Nevertheless, these considerations are not limited to prioritize tie contradictions. If solving a dominating contradiction exceeds existing technological capabilities, experts might focus on a dominated one even if it is less of a priority to delight customers and achieve competitive advantages.

In sum, most of the contradictions are potential areas and overcoming them lead to innovative improvements. Some contradictions need considerable time to pursue SBCE process for and some need less time. However, using the Figure 7.8 and Figure 7.9 the experts of AHS will have a rough understanding of which contradictions to target. They can also plan to conduct SBCE to offer innovative AHS in short or long terms bases.

### **7.3.1.6**      *Map contradictions to design factors*

Once the contradictions are identified and prioritized, the next is to map the contradiction to the product's subsystem, components and the associated factors (e.g. material types, configuration types, number of components, etc.). Every contradiction is related to one or more of the humidifier design characteristics which the designers can have influences to change. Therefore, to complete the SBCE IR, the contradictions are mapped to the product subsystem elements (or what sometimes called trade-space) as shown in Table 7.11, below.

The trade space is coded according to a subsystem code, function, elements, and factors. C (Cabinet), Rack (R), and Drop Separators (DS) are general subsystem of the AHS. Then, the functions that each general subsystems do are assigned a code (LP = low pressure, HP = high pressure, M = modulate, D = drain and so on).

The lower level sub-systems and components that are necessary to execute the desired functions are mapped as numbers. For example, CHP2, is a pump that should be in a cabinet and uses for pressuring the water in high pressure (HP). RM1 is a valve type that is assembled in the Rack to modulate or control the water flow into the manifold of the Rack. Using the mapping of contradictions to sub-systems/components on can clearly see critical components that need innovation. For instance, contradictions from T1 to T6 are all related to similar components (CHP2 = pump, CMEP = PLC, programmable logic controller, RH1 = nozzles, and RM1= valves normal closed). These components are highly integrated. Thus, during SBCE implementation, exploring solutions to solve the contradictions requires seamless integrations between the subsystems specialists. Moreover, testing and developing of limit-curves are tightly related to the performances of these components, indicating who should be involved in SBCE implementation process.

Table 7.11: Mapping contradiction to AHS.

Contradictions	Fun	F <sub>down</sub>	Rank	Adiabatic Humidifier Subsystem															
				Cabinet (C)								Rack (R)				Drop Separator (DS)			
				Function															
				LP	HP	MEP	MC	SEP	SC	FS	H	M	D	TD	AF	FS	D	SHD	M
T1	P2	P4	(1,3)		2											1			
T2	P4	P5	(3,0)		2	6										1	1		
T3	P4	P6	(3,0)		2											1	1		
T4	P5	P6	(0,0)		2											1	1		
T5	P2	P8	(1,4)		2	6										1	1		
T6	P4	P10	(3,6)		2											1	1		
T7	P2	U3	(1,1)			2		2								1	1,2		
T8	U3	C1	(1,4)							1,2,4									
T9	U3	C2	(1,6)														1		
T10	A4	C2	(1,6)														1		
T11	P3	C3	(7,3)		1														
T12	P10	C3	(6,5)		2														
T13	P11	C3	(2,5)		1,2	5	1												
T14	A1	C3	(0,5)		2														
T15	A3	C3	(2,5)	1to 11	1to 14	1to 14	1												
T16	P4	C4	(3,3)													1	1 2		
T17	P6	C4	(0,3)							1,2	2,5								
T18	P8	C4	(4,3)							1	1								
T19	A4	C4	(1,3)													1	1 2		
T20	C1	C4	(4,3)													1	2		
T21	C5	C5	(2,2)							1to 4							2		
T22	A1	M1	(0,1)		2											1	1,2		
T23	A4	M1	(1,1)		2														

### 7.3.1.7 Plan for SBCE to overcome contradictions

The SBCE IR is a very powerful and strategic instrument for the industry to plan efforts to pursue SBCE. The rules developed and the mapping activities complete what has been taken as a prime objective of this chapter. Experts of AHS can use the information posed in Figure 7.8 and Figure 7.9 and Table 7.11 to make rational choices to start SBCE implementation. Therefore, SBCE IR helps designers as a systematic guide to narrow-down design improvement initiatives that can be handled by SBCE.

The SBCE IR is developed considering criteria such as customer importance and competitive advantages. However, there could also be other criteria experts might need to consider in selecting contradictions such as the technological capabilities, resource required and efforts needed to overcome contradiction using SBCE process.

In the next section, a pilot to conduct an SBCE process for a contradiction (T21) will be presented. The purpose of the next section is to experiment on how to use the SBCE IR to further pursue SBCE process.

### 7.3.2 SBCE on Rack subsystem

Designers and managers organized a workshop in order to select a contradiction to begin a SBCE process. T21 has been selected by designers. Looking at Figure 7.9, the contradiction considered is dominated by T7 and T23 and is in tie with contradictions (T9, T10, T18 and T19). However, considering the time available within the period of this thesis, T21 has been chosen to start because of overcoming it in SBCE process takes considerably less time than the other contradictions that dominates it or tie with it in rankings.

The designers noted that, some contradictions take longer time to solve taking a SBCE paradigm. For example, the contradictions T1 to T6 which are related to contradictions between technical performances (P1, P2, P3, P4, P5 and P6) are harder to solve in short term. Because, the product structured is defined around accepting the tradeoffs in between the requirements. Taking T1 as example, the contradiction is between *Multi-zone up to 12* and *Modulation range*, implying that it is not possible to increase the number of zone areas the humidifier can serve, and at the same time increase the modulation range or the capacity of water flow (liter per hour), because an asynchronous motor that runs the pump in the current design has limitation to do so. The current number of zones the humidifier can serve is 6, and the customers want to increase the number to 12. The current modulation range the humidifier has is between 30 l/h (liter per hour) to 50 l/h, and the customers want to have a range between 1 l/h to 50 l/h (the wider the range the better performance). The minimum motor speed in the current design is 14% of its maximum speed (2400 rpm, revolution per minute). At this minimum speed and below, the quality of modulation (water flow) is low; because the humidifier start spraying water more than needed (the water flow should increase in steps rather than jumping to a higher flow). Given this constraint, one possible solution is to have two different pump types. One that work at lower speed so as to achieve a good level of modulation at low speed, the other that works at higher level of speed to expand the number of zones (the higher the number of zones, the higher speed required to arrive to different areas or zones). This solution doesn't avoid the inherent contradiction. Having two pumps costs more. In fact, it creates another contradiction with another requirement (C3 – *pump cost reduction*). Another solution was proposed using the TRIZ principle called “changing parameter” (Altshuller 1984, 1994, 1999). That is, to have a motor speed that extends the range of speed from 0 to 2400 rpm, so that it solves the contradiction to have both higher numbers of zones and at the same time higher level of modulation at lower speed (14% of the max). However, this solution needs more time to develop (up to 1 year) and to communicate with suppliers to obtain their support in the innovation.

On the other hand, the selected physical contradiction T21 (between requirement non-VDI Rack (C5) and with itself) can be solved in short term (1-2 months). The contradiction is explained as follows: the current AHS design is compliant with European hygienic requirement called VDI6022. However, the company is expanding its business to different business applications or markets such as Tabaco industries, painting shops

of automotive industries and in different emerging countries (e.g. China and Brazil). In this market (let's call this market as non-VDI market) there is no mandatory VDI6022 compliancy requirement. Moreover, these customers are requiring cheaper design and there are non-value adding features in the current design that have no value for non-VDI market. Therefore, the purpose is to overcome this contradiction to satisfy both types of markets (VDI requiring market and non-VDI market). The framework used in this thesis and also in the company to address the contradiction is summarized in Figure 7.10.

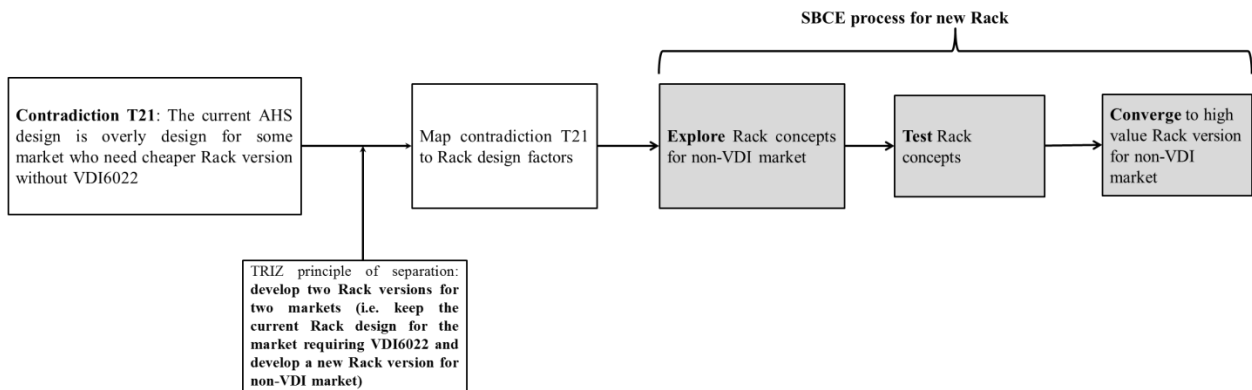


Figure 7.10: SBCE framework to overcome T21.

In order to overcome the contradiction, the company agreed to use the TRIZ “*principle of separation*” (Altshuller 1984, 1994, 1999). That is to separate the product version for two markets (VDI and non-VDI markets). This implies that, the current AHS design will be offered to VDI market and a new version has to be designed for non-VDI market.

Therefore, the role of SBCE is to design a new Rack version for non-VDI market. In this thesis, the reports in the next sections focus on the activities done to conduct the SBCE for new Rack version, i.e.: exploring of design concepts which can minimize the costs of the Rack for non-VDI Rack market; identify key constraints to test Rack concepts explored; test Rack concepts for constraints; and converge into a Rack concept that maximizes the value for non-VDI customers.

### 7.3.2.1 Basics of Rack subsystem and mapping T21 to design factors

Before going in detail with the SBCE process, in this section the basic working principle of Rack and its components are explained. Moreover, the identified design factors by experts that need to be changed to overcome T21 are identified in this subsection.

The right side of Figure 7.11 shows the Rack schematic diagram with the components. The left side of Figure 7.11 shows the mapping of contradiction T21 to Rack design factors.

The simplified working principle of the Rack subsystem is as follows: highly pressurized water (about 70 bars) will be pumped from the pumping unit or Cabinet (motor and pump, see Figure 7.5) to the solenoid modulating valves which are normally closed (see Figure 7.11, #4). These valves pass the modulated water to the Rack distribution system. Because the water pressure inside the Rack will increase to a desired level step by step, the modulating solenoid valves are connected with each other using flexible hoses (i.e. when the water flow reaches the last manifold column, the desired pressure will be achieved). Then, the water passes through the vertical manifolds (see Figure 7.11, #6), and sprayed out to a room through nozzles (see Figure 7.11, #2). Empty holes which are used to clean the Rack will be covered by cups (see Figure 7.11, #6). Finally, once the Rack finishes operation, the water leaves the Rack distribution system through the solenoid drain valves (see Figure 7.11, #9).

Mapping contradiction 'non-VDI rack' to rack design factors			
Components	Functions	Design factors	
#1, #7	Frame and bracket	Support and simplify cleaning operations	Number of frames and brackets
#4	Modulating valve	modulate	Number of valves for a manifold
#5	Flexible hose	Transfer high pressure water	Number of hoses
#9	Drain valve	Drain water	Material type of drain valve
#6	Holes and cups on manifold	Simplify cleaning operations	Number of holes and cups to use

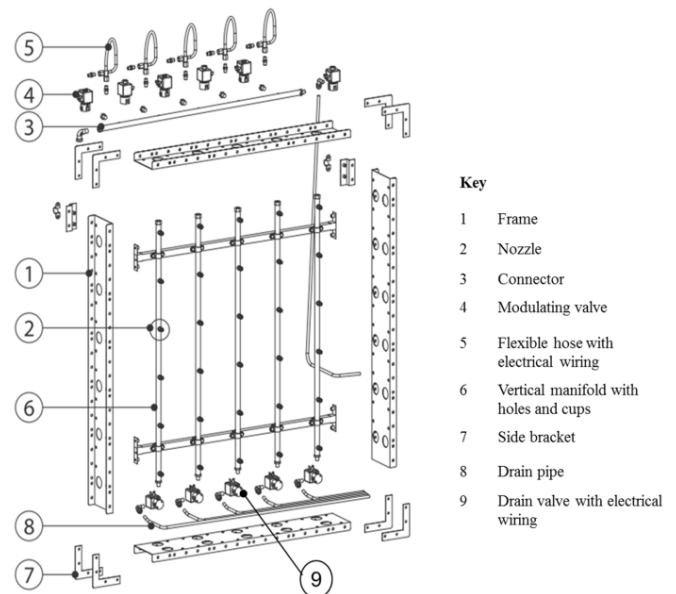


Figure 7.11: Rack components and mapping contradiction T21 to Rack design factors.

### 7.3.2.2 Exploration of Rack concepts for non-VDI market

Designers of the Rack subsystem conducted more than three workshops to explore alternative design solutions to reduce costs of the Rack for non-VDI market. After brainstorming on several sessions, designers explore four different concepts for the new Rack version: (a) frameless Rack, (b) changing the solenoid stainless-steel drain valves to mechanical brass valves, (c) using one solenoid modulating valve for two manifolds, and (d) eliminate the number of cups and holes on the manifolds. The summaries of the advantages, disadvantages, tests required of the concepts generated are given in Table 7.12.

(a) **Concept 1:** is to remove the non-value adding stainless-steel frames (see Figure 7.11, #1) and side brackets (see Figure 7.11, #7) in the Rack structure which are very expensive for non-VDI market. Most

of the non-VDI customers are industrial facilities, the frames and brackets added in the current Rack design are not necessary. The metal frames that are used to slide the Rack into an AHU unit (Air Handling Units) are needed when cleaning operation is desired. However, thanks to the separation of the markets, the frames are removed as non-value adding because the non-VDI Rack doesn't need removal from the AHU unit for cleaning, and can be welded (fixed attachment with AHU) by the users themselves. The cost advantage of this concept is estimated by the AHS experts to be 10% of the Rack cost, including material and assembly operation costs.

- (b) **Concept 2:** is to substitute the electronic stainless-steel solenoid drain valves (see Figure 7.11, #9) with mechanical valves (brass material), which are used to release water once the Rack finishes operation. The VDI hygienic requirement dictates materials to be made of stainless-steel that are in contact with the water. However, once the markets are separated, the non-VDI Rack version will not require this material. Thus, an alternative mechanical and cheaper valve which is made up of brass (copper and zinc) can be used. The market prices for the stainless steel and brass valves are 18 €/piece and 5 €/piece respectively (a cost reduction of 13 €/piece). Moreover, since the VDI requirement demands a close control on the water quality inside the Rack, the drain valves are connected with the PLC (Programmable Logic Controller, see Figure 7.5) using electrical wiring. But, these wirings will not be required in the new Rack version. Thus, the cost advantages of this concept come from reducing the material and wiring costs. Mechanical brass valves are less corrosion resistant than stainless-steel valve, but brass material will corrode within a longer period of time. Therefore, the valve type is a better candidate for the new Rack design.
- (c) **Concept 3:** the third concept is to reduce the number of modulating solenoid valves (see Figure 7.11, #9) by assigning one valve for two vertical manifolds (see Figure 7.11, #6). This concept enables cost reduction by minimizing the number of valves and associated wiring costs used to connect with the PLC system. The price of each valve is about 20 €/piece. The cost advantages vary depending on the size of the Rack, the smaller and the biggest sizes have 4 and 30 manifolds respectively. Therefore, the average cost savings per Rack are estimated to vary from 40 €/Rack to 3000 €/Rack.
- (d) **Concept 4:** the last concept is to eliminate the holes and the cups on the manifolds (see Figure 7.11, #6). In the current design, the empty holes were used to clean the manifolds when it is thought to be dirty (requirement of VDI). However, in non-VDI version the holes and the cups (to close the holes) have no functions. So they are eliminated as non-value adding features. The advantages of the concept are to minimize cups' costs and reduce time for drilling the holes during manufacturing process.

Table 7.12: Summary of Non-VDI Rack concepts generated, advantages, disadvantages, and tests required<sup>31</sup>.

	Concept 1	Concept 2	Concept 3	Concept 4	Concepts merging <sup>32</sup>
Improvement	Remove frames	from stainless steel to brass valves	One solenoid valve for two manifolds	Remove holes and cups on manifolds	Combination of concepts 1, 2, 3, 4
Advantages	10% cost reduction	- 13 € saving/piece - less administrative costs - less electrical wiring cost	- reduction of valves (20 € saving for each valve reduced) - less electrical wiring cost	- reduction of cup costs - reduction of drilling operation time	30% cost reduction compared to the current Rack design
Disadvantages	none	corrosion of brass	less water spray quality	none	corrosion, less water spray quality
Test required	no	- max. pressure resistance - min. pressure to open	flow rate test	no	final functional test

The four concepts generated are subject to improving the current Rack design to suit to non-VDI market. The SBCE IR helps designers to identify the need for satisfying this market by offering cheaper Rack. As noticed, the explored concepts are small modifications on the current design. The SBCE process to follow is narrowed one in terms of the design space considered. Nevertheless, the experts estimate a considerable cost advantages for non-VDI market. This cost benefits has been obtained by removing non-value adding features and associated manufacturing operations which have been designed into the existing AHS design. The next step in SBCE process is to test the concepts for the constraints identified in Table 7.12.

### 7.3.2.3 Testing Rack concepts

In SBCE process, the evaluations or testing of concepts for constraints are important to facilitate the ‘test & then design’ paradigm (Kennedy and Harmon 2008). This paradigm in SBCE is paramount to anticipate failure modes early in concept generation phase to check feasibilities of alternative solutions. Therefore, for each Rack concepts generated, the sources of failures are identified as shown in Table 7.12 to test them

<sup>31</sup> All the data reported on the cost advantages are based on estimation obtained from the experts of AHS. Note that the cost advantages address only for non-VDI market not VDI market.

<sup>32</sup> Since the concepts generated can be combined the concept merging is referred to combining all the concepts into one.



before going to detail design phase. Concept 2 needs ‘pressure test’ and concept 3 needs ‘flow rate test’. The evaluations of the concepts for constraints done by the AHS experts are explained as follows:

- Pressure tests for concept 2:** the mechanical brass valve proposed for drain valve has never been used before, and need to be tested for the maximum pressure it can withstand, and the minimum pressure at which the valve will close. The working pressure of the Rack is 70 bars. The maximum allowed pressure in the Rack system could be +10% of the working pressure. So, the new valve should withstand the deviation from the nominal working pressure. Moreover, the minimum pressure that the valve (which is normally open) will close should be investigated. If the minimum pressure that makes the valve close is higher than 0.5 bar, there is the risk that the valve will not close when it is needed, and water kept draining. Three new valves are sourced from three different alternative suppliers. The components from the three suppliers are tested for hours (this type of test is called life test in the industry. Figure 7.12 shows the limit curve of the pressure test of components from each supplier. As shown in the figure, supplier 2 has passed the upper and lower pressure constraints. Since the prices from all the three suppliers are similar, the only consideration to choose among the suppliers is the passing of the constraints. Therefore, supplier 2 is taken as the candidate to supply the drain valve for non-VDI Rack design.

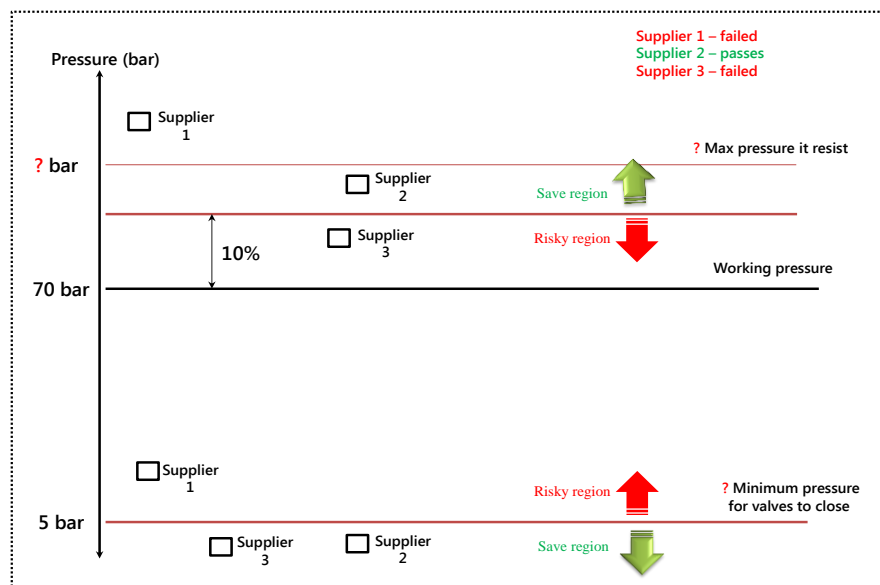


Figure 7.12: Limit curve for pressure test of mechanical drain valves and suppliers evaluation.

- Flow rate test for concept 3:** when one valve substitutes two valves, the maximum desired water flow of 100 l/h should be able to pass through the single valve to serve the nozzles on the two manifolds (see Figure 7.11, #6). If the concept is not able to deliver the required amount of water to manifolds, pressure drop will be the risk. Pressure drop occurs when the required pressure is not achieved while the nozzles

spray the atomized water. Pressure drop creates low quality of precision. The concept has been tested, and able to allow the maximum water flow when the number of manifolds is more than 5. Thus, the concept works very well when the number of manifolds is more than five.

#### **7.3.2.4 Merging Rack concepts**

All the four concepts are combined to maximize the benefits or the value of the new Rack version. Concept merging is synonyms the convergence process in SBCE. The final merged concept is estimated by designers of AHS to have a 30% less cost than the current Rack design considering all the cost advantages of the concepts generated. After final functional test, the company is expecting to launch the new Rack design to customers soon. Moreover, the new version is expected to have high market share since no competitor has a non-VDI Rack (see the competitors' performances of C5 on Figure 7.6).

### **7.3.3 Assessment of SBCE IR by AHS experts**

The SBCE IR is tested in AHS case study and the roadmap for this particular system is developed. Moreover, using the roadmap SBCE process has been experimented on Rack subsystem which shows the relationships between SBCE IR and SBCE process. The new Rack design will have significant cost advantage for non-VDI customers. The experts estimate a 30% cost reduction from the new Rack design for non-VDI customers. The SBCE experiment on Rack subsystem is a narrow one. The number of components explored and the configuration proposed are few in numbers. However, most of the identified and prioritized contradictions are potential projects the company can launch in short and long terms.

In order to verify and assess the potentials and limitations of the SBCE IR for the company an open questionnaire is prepared. The questions in the questionnaire are categorized in three classes: (i) *differences and synergies with existing methods used in the company*, this is to understand what is the existing method the company follows to identify improvement areas for new projects and investigate the differences and synergies with SBCE IR methodology; (ii) *effectiveness of SBCE IR*, this is to measure if the SBCE IR achieves its objectives in terms of reducing the extensive nature of SBCE process, its effectiveness to identify improvement areas for SBCE, its effectiveness in evaluating customer value, its effectiveness in evaluating competitors' products and its contribution to enhance innovation at early phase of design; and (iii) *simplicity/ difficulties/ scalability/skills and capabilities needed to build SBCE IR*, in this category the aim is to measure the efficiency of building the SBCE IR methodology in the case company. Interviews are made with four experts who are knowledgeable about technical, market, business and improvement related issues in the company. The interviews are made individually with each expert. The experts are extensively involved in building the steps of SBCE IR for AHS system and are knowledgeable about the existing practices in the

company. Table 7.13 summaries the response of the experts in assessing the SBCE IR. The following subsections elaborate the results of the assessment briefly.

### **7.3.3.1 *Differences and synergies with existing methods used in the company***

The questions asked in this category is to identify the differences of SBCE IR with methods that are used in the company and to meter the value the company can obtain in adopting the SBCE IR methodology.

Before any new products are developed the company uses different methods to identify and select projects (improvement areas) to pursue. These methods are: new market requirements (that is when customers are requesting improvements for products), correction of previous mistakes (this is related to when failures on products occur during use, the company initiate new projects to fix problems), technology push (this is related to internal initiatives to design new products and technologies), company strategy (this is related to long term plans of the company in terms of new products to develop, new markets to enter and so on) and portfolio management (the company has a formal portfolio management process to prioritize and select projects coming from new customer requirements, correction of mistakes, technology push and company's strategy).

#### **➤ Problems with existing methods used in the case company**

The existing methods used in the company to identify and prioritize projects for new products have the following drawbacks:

- *Existing methods are not structure*: the dominate sources used to identify new projects in the company are reactive to external changes. For example, new requirements emerging from customers can happen any time and the company has to react to these requests to plan new projects. Projects that are initiated to fix corrections are also highly unpredictable and can happen at any time. The only existing method that can be used as proactive is from technology push. However, this method leaves the company to be dependent on few and highly experienced designers who can have imagination to initiate new technologies to be developed. Technologies push can be very random method where ideas for new product development projects arise at any time. Therefore, the existing methods make the company to react to changes and leave less flexibility to make effective and efficient planning. As a result, the product development organization becomes disruptive.

- *Existing methods are based on top-down approach:* the portfolio management is used in the company to prioritize projects. However, there are limited information related to customer importance, competitive priorities and resource availability to make effective selection of project ideas for new products. These leave planners to base their choices based on experience. In a sense there is discontinuity between strategic planning at portfolio management level and technical level. This often results in selecting wrong projects or eliminating the right projects for new products to be developed.
- *Existing methods are not based on contradictions:* project proposals for new products are not to overcome contradictions. Often what seems to be simpler or available ideas are chosen. This limits the potential of the company to offer innovative products to customers.

➤ **Benefit and synergies of SBCE IR to support existing methods**

The experts identified the following key benefits of SBCE IR and possible synergies between existing methods:

- *SBCE IR will make existing methods structured and proactive:* using the methodology improvements on products or new projects can be planned and resource requirements can also be anticipated beforehand. The SBCE IR methodology provides contradictions and their priorities. Thus, new projects can be planned according to the resources available and based on their priorities. Since requirements forming contradictions are collected and evaluated, the company can benefit to be proactive to emerging requirements and technologies.
- *SBCE IR is based on bottom-up approach:* using the roadmap build for products, planners involved in portfolio profiling can use the SBCE roadmaps to make informed decisions to select project proposals. Since the SBCE IR contains information from customer, market, technical and resource perspectives, it enables planners to plan for innovative projects for short and long time horizons.
- *SBCE IR focuses on contradictions:* focusing on contradictions, and then overcoming them using SBCE's principles will improve the innovation process in terms of methodological structure and generate innovative ideas. Of course the identification of contradictions doesn't mean that designers can innovative. However, it gives them the opportunity to overcome specific contradictions. Moreover, identification contradictions surface challenges to address and improvements to make. In order to help them to solve contradictions, methods such as TRIZ's principles and tools can be used.

Figure 7.13 summarizes the benefits and synergies between existing methods used in the case company and the SBCE IR methodology.

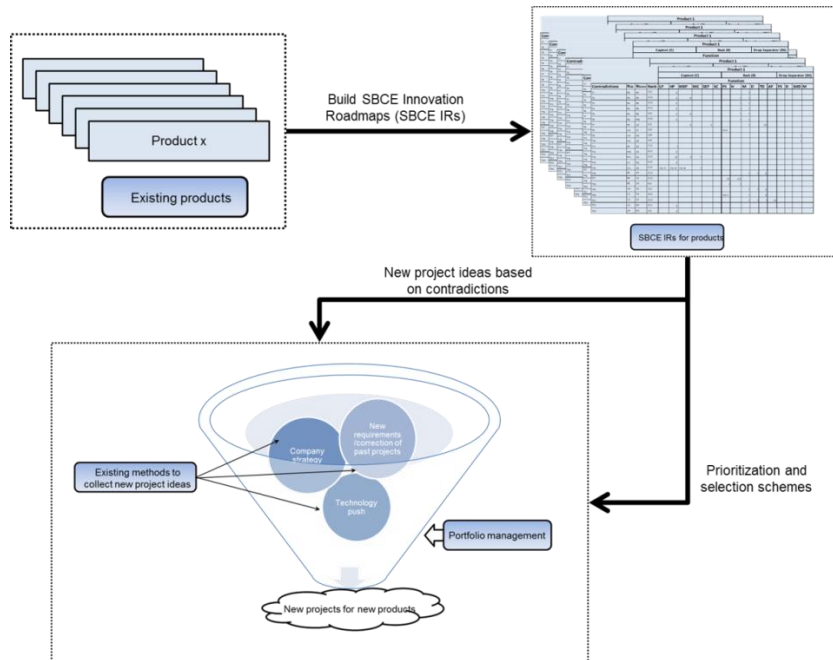


Figure 7.13: Benefits and synergies of SBCE IR and existing methods used in the case company.

### 7.3.3.2 Effectiveness of SBCE IR

The questions asked to experts to assess the effectiveness of the SBCE IR methodology can be categorized in four aspects: *the effectiveness of the methodology to reduce the extensiveness of SBCE process, the effectiveness of the methodology to identify improvement areas and to evaluate customer value, the effectiveness of the methodology to evaluate competitive products and the effectiveness of the methodology to enhance innovation.* The questions are selected based on the main objectives of the SBCE IR and the criteria used to build it. The response results are summarized as follows:

- *SBCE IR and extensiveness of applying SBCE:* the experts acknowledge the effectiveness of the SBCE IR methodology in terms of its ability to help them focalize where SBCE should be applied. The focus on contradictions and the prioritization rules provided in the SBCE IR contribute to the effectiveness. However, the experts also noted that, SBCE should be used as a rough-cut planning methodology than to make final decisions on which contradictions to solve. Other sources should also be taken to make final decisions on which area to improve (e.g. company's strategy should also be considered as one criterion to select contradictions for SBCE).

- *SBCE IR and evaluating customer value for improvements:* the experts appreciate the use of AHP method to evaluate customer importance. This helps them to systematically evaluate the requirements. However, the experts underlined two important considerations to take during the customers' requirements collection step of the SBCE IR. First, the list of requirements should also include future predictions on emerging needs. Otherwise, the SBCE IR becomes unstable since customers often changes requirements or new requirements emerge. Therefore, designers and managers building the roadmap should make careful investigations on the future needs and they should create close collaborations between customers to identify list of requirements. The second note is related to the variety of customers the case company should satisfy. The case company has multiple levels of customers which often have different importance on a single requirement. Taking AHS product for example, there are four layers of customers: *Contractors*, who buy large number of the product from the case company; *Installers*, who buy the product from contractors and install it at customer sites; *OEMs*, who directly buy the product from the case company; and *Final customers*, who are using the product. These customers have different needs and importance. For example, Contractors are more interested in cost or price, Installers are more interested in on easiness to install, OEMs are more interested on technical performances and Final customers are more interested in technical performance or simplicity to use. Therefore, while assigning judgment on the importance for requirements in the first step of SBCE IR, care must be taken to balance the needs of the different customer types.
- *SBCE IR and evaluating competitive products for improvements:* the experts acknowledge the effectiveness of the SBCE IR in evaluating competitive products. Moreover, using SBCE IR for sure lead them to produce products that have better performances than competitors. However, the experts noted a drawback. Basing innovation roadmap based solely on benchmarking competitors' performances limit innovativeness of designers. Designers might only do improvements just to beat competitors and no more. This aspect needs attention.
- *SBCE IR and enhancing innovation:* four questions were asked related to the effectiveness of the SBCE IR to enhance innovation during exploration phase of SBCE process. The effectiveness of idea generation phase can be measured taking four measures (Shah and Vargas-Hernandez 2003): *quantity*, is a measure of the total number of ideas generated; *quality*, is a measure of the feasibility of an idea and how close it comes to meet customer requirements; *novelty*, how unusual or unexpected an idea is as compared to other ideas; and *variety*, is a measure of the explored solution space during the idea generation process. For quantity and variety the experts agree on the effectiveness of SBCE to enhance these measures. In particular, if the idea

generation process in SBCE is supported by methods such as TRIZ, designers will have the opportunity to structure design problems to explore number of ideas as well as good varieties among the ideas. For novelty and quality, designers acknowledge that SBCE IR contributes to improve these measures. However, the experts noted that, novelty and quality largely will depend on the experience and imaginations of the designers who are overcoming contradictions. Thus, there are rooms that personal skills and experiences will affect the effectiveness of SBCE IR.



### 7.3.3.3 *Simplicity/ difficulties/ scalability/skills and capabilities needed to build and use SBCE IR*

The final aspect of the assessment is related to the simplicity/ difficulties/ scalability/ skills and capabilities needed to build and use the SBCE IR. The responses of the AHS experts are summarized as follows:

- *Simplicity/ Difficulties of building SBCE IR*: all the experts interviewed said that it is not difficult to build the SBCE IR for products. But, they said that it is time consuming to collect data to build it. They suggest possible remedies to tackle the problem. The first one is to have simpler SBCE IR version for small and simple projects and the full SBCE IR for large and very new products. The second recommendation given is to use SBCE IR for modules or platforms which are shared by many products. In this way, it will be less time consuming, and also make the SBCE IR robust to changes in customer requirements and technologies. Normally, standard modules or platforms are stable in terms of change in requirements and technologies.
- *Scalability*: this question is to check if the SBCE IR can be built for any product. Experts find no reason to apply it for mechanical or electronic products. However, when the product becomes complex, building SBCE IR might consume time.
- *Skills and capabilities needed to build SBCE IR*: there are several skills and capabilities needed to build and use the SBCE IR. Among which the following are reported by the experts: (1) *SBCE expertise*, designers should have a good understanding on the principles of SBCE and training on how to explore, communicate and make converge based on sets; (2) *Process knowledge*, people who build SBCE IR should have a good understanding of the product development process starting from customer value research to all the lifecycle of a product. Otherwise, many possible flaws can occur in collecting data and conducting the steps of SBCE IR; (3) *TRIZ training*, as SBCE IR is based on analyzing contradictions, designers should have good understanding and knowledge on how to apply TRIZ's principles and tools to overcome contradictions. This skill are not available in the case company but will be needed to make SBCE IR more usable.

Table 7.13: Summaries of SBCE IR's assessments by AHS experts.<sup>33</sup>

Aspects	Questions	Summary of interviews responses
Difference and synergies with existing method used in the company	What is/are the current method/s to identify improvement areas for new products?	New market requirements, corrections of previous mistakes, technology push, company strategy that define the evolution of products, portfolio management to prioritize projects.
	How different existing methods are compared to SBCE IR?	<ul style="list-style-type: none"> <li>❗ Existing methods used in the company are not structured, difficult to plan for emerging/changing marketing requirements and correcting previous mistakes, technology push could also be random.</li> <li>❗ Existing methods are top-down approach and often have limitation in planning projects based on real customer benefits, competitors' analysis and resources availabilities.</li> <li>❗ Existing methods in the company are not focusing in contradictions rather they concentrate what is easy to change. This might limit the potential of offering innovative products to customers.</li> <li>✅ SBCE IR is proactive rather than reactive and improvements on products can be planned and resource requirements can also be anticipated beforehand.</li> <li>✅ SBCE IR is bottom-up approach in which designers and project managers can use SBCE IR to propose improvement projects to top management during strategic and portfolio planning.</li> <li>✅ SBCE IR can be integrated with existing methods. It helps to structure the existing methods (to effectively identify improvement projects) and support portfolio profiling or prioritizing.</li> <li>✅ SBCE IR is based on identifying contradictions and overcoming them using SBCE process. Focusing on contradictions is new way of working for the company but enables us to advance product technologies and excite customers and achieve higher market share compared to competitors.</li> </ul>
Effectiveness of SBCE IR	Does SBCE IR able to reduce the extensiveness nature of SBCE by prioritizing contradictions or tradeoffs as improvement areas?	<ul style="list-style-type: none"> <li>✅ Yes, SBCE IR helps us to define where innovation should takes place. Moreover, the prioritization scheme will help us to know what type of improvements or projects should be launched.</li> <li>❗ However, SBCE IR should be taken as a rough planning scheme, and then management should give more detail planning to prioritize contradictions based on company's strategy.</li> </ul>

<sup>33</sup>  positive feedback for SBCE IR;  limitation of existing methods used in the company or limitation of SBCE IR.



<p>Is SBCE IR effective in identifying improvements areas for SBCE</p>	<ul style="list-style-type: none"> <li>✔ Yes, the first step of SBCE IR is to identify and assign importance of customer requirements. The AHP method used helps us to systematically weight the requirements to satisfy our customers.</li> </ul>
<p>Is SBCE IR effective in evaluating customer value?</p>	<ul style="list-style-type: none"> <li>✔ However, customer requirements that are feed to SBCE IR should reflect the future needs of customers; otherwise the plan becomes unstable if customers frequently change their requirements. In order to make SBCE IR a robust planning methodology, designers and managers should study very well the current and emerging requirements in close collaboration with customers.</li> <li>❗ It is also important not to make inaccurate judgment about customers. Carel Industries is operating in a market where there are different levels of customer types (e.g. installers, contractors, OEMs and final customers). These customers usually have different importance for a requirement of a product. Therefore, in building SBCE IR the weighing of customer requirements should take care of balancing the needs of the different customer types.</li> </ul>
<p>Is SBCE IR effective in evaluating competitive products?</p>	<ul style="list-style-type: none"> <li>✔ SBCE IR is effective in evaluating competitors' product. So that, we can make sure that we stay competitive in the competitions by offering better products.</li> <li>❗ However, taking competitors' evaluation solely as a criterion to build SBCE IR has limitations to foster innovation. Often, innovative ideas might arise from internal or personal initiatives. Thus, improvement products better than competitors might lead designers to do only low level innovations just to beat competitors.</li> </ul>
<p>Will SBCE IR help to the quantity of ideas or concepts to generate (<b>quantity</b>)?</p>	<ul style="list-style-type: none"> <li>✔ Yes, SBCE IR creates more opportunities for designers to increase number of solutions because of specific problems given to them to overcome.</li> </ul>
<p>Will SBCE IR help to increase the quality of conceptual ideas to generate (<b>quality</b>)?</p>	<ul style="list-style-type: none"> <li>✔ Yes, if the customer requirements are well captured and evaluated in SBCE IR, it will help us to satisfy and also excite customers by overcoming contradictions. Moreover, the principles of SBCE increase the success of concepts to be feasible and to meet customers' expectations.</li> <li>❗ However, to improve quality of ideas, we need personal experience and ambitions of designers to explore concepts which can overcome contradictions.</li> </ul>
<p>Will SBCE IR help to identify novel ideas or concepts (<b>novelty</b>)?</p>	<ul style="list-style-type: none"> <li>✔ Yes, if we use TRIZ principles and tools, SBCE IR increases the chance of having novel ideas which might be out of the box.</li> <li>❗ However, to improve novelty of ideas, we need personal experience and ambitions of designers to overcome contradictions in SBCE process.</li> </ul>

	Will SBCE IR help to increase variety of concept to generate ( <b>variety</b> )?	<ul style="list-style-type: none"> <li>✔ Yes it creates variety in idea generated if it is supported by TRIZ principles and tools to overcoming contradictions.</li> </ul>
Simplicity/ Difficulties/ Scalability/Skills and capabilities needed for SBCE IR	Is building SBCE IR easy for a product?	<ul style="list-style-type: none"> <li>✔ Not difficult.</li> <li>❗ But time consuming, in terms of data collection.</li> <li>❗ Therefore, SBCE IR can be simplified by taking simpler version for small projects and full version for large projects.</li> <li>❗ Another way to simplify it will be apply it on modules or platforms that are shared by different products. In this way, it will be possible to share an SBCE IR by many projects and stabilize it (since customer requirements are stable for modules).</li> </ul>
	Is SBCE IR applicable to other products?	<ul style="list-style-type: none"> <li>✔ Yes, the SBCE IR is applicable irrespective of product types.</li> <li>❗ But it might be time consuming for big and complex products.</li> </ul>
	Can SBCE IR be applied for product platforms or modules?	<ul style="list-style-type: none"> <li>✔ Yes, is might be effective to apply SBCE IR at module levels that can be shared across products. This might reduce the time to construct SBCE IR and make it robust to changes in customer requirements and technologies.</li> </ul>
	What skills and capabilities are needed to use SBCE IR?	<ul style="list-style-type: none"> <li>❗ SBCE expertise, vision on the development process from customer requirement collection phase to the whole life-cycle of a product, TRIZ training, knowledge about customers and application areas where a product is used.</li> </ul>

## 7.4 Conclusions, limitations and future researches

The main purpose of this chapter has been to propose a systematic methodology that guides designers to make rational choices to start SBCE implementation projects. Researches show that companies have failed and obtain negative performance results trying to implement SBCE. One of the rationales of such negative results can be attributed to its extensive nature to apply it to a product. The other reason is that, there is no systematic methodology that currently exists to support designers and managers to make effective and rationale choices about where SBCE projects should focus on. Thus, SBCE is an extensive process that demands a careful investigation upfront before deciding on which area to apply it. The SBCE IR methodology developed in this thesis answers these particular shortcomings in practice and academia.

The SBCE IR methodology is based on identifying and prioritizing contradictions in a product system. Contradictions are taken as a central element of SBCE IR. According to TRIZ (Theory of Inventive Problem Solving) identifying contradictions between requirements is taken as gate ways for product innovation. The existing literature on SBCE has been focusing on tradeoffs but in practice this leads to accepting compromises and as a consequence limits innovation. Moreover, understanding and modeling tradeoffs

between alternative sets are challenging in particular for small or medium sized companies where there is little resources/ capabilities. Therefore, SBCE IR benefits from synergies between SBCE principles and TRIZ concept of contradictions.

To develop SBCE IR, three additional criteria and assumptions are taken to prioritize contradictions: customer value information, competitive advantages and resources/ capabilities. The criteria are used to evaluate customer requirements, competitor performances, and consider the resource capabilities of the company to solve design problems.

The SBCE IR involves six steps and each step is supported by common tools and methods found in literature. To structure the steps of the SBCE IR, QFD (Quality Function Deployment) method is used. The first step is to identify customer requirements and assign importance. AHP (Analytical Hierarchical Process) is used to assign weights to customer requirements. The second step is assess competitors' products and set targets for each requirements identified. The third step is to identify technical and physical contradictions in a product system. The fourth step is to identify causal relations between contradictions to sort out dependent and independent contradictions. DEMATEL (Decision Making Trial and Evaluation Laboratory) method is used to find the causal relations between the contradictions in the fourth step. In the fifth step rules are derived to prioritize contradictions based on the information obtained from previous steps. For dependent contradictions the roots will be given high priority for SBCE implementation. For independent contradictions rankings (derived from steps 1 and 2) of their contradictory requirements are used to prioritize them for SBCE implementation. The final step is to map prioritized contradictions to design factors to being SBCE process to improve a product. This final step should be done by experts designing and developing the product.

Three validations have been made to test the SBCE IR, to use it to experiment an SBCE process and to assess the pros and cons of the SBCE IR methodology by experts.

First, AHS was taken as case study to apply the SBCE IR. In fact, strong collaboration has made with the AHS experts to collect the data to build the roadmap. Several contradictions were identified in the system, some contradictions are between technical performances, some are between business related performances and some are between technical and business related performances.

Second, based on the roadmap, designers choose a contradiction called non-VDI Rack (T21), and begun experimenting SBCE process. The contradiction was easier to solve in short time compared to other identified contradictions. Designers conducted workshops to explore Rack concepts that can minimize the cost of the Rack for those customers who don't need a VDI hygienic requirement. Four concepts were explored, and tests were conducted if the concepts work. Finally, the concepts were merged to create a high

value Rack that has significant cost reduction with respect to the current design. The experts estimate a 30% cost reduction of this new Rack for non-VDI market. This Rack is under development to be launched soon.

Third, an open questionnaire was provided to four experts to assess the SBCE IR using interviews. The experts are highly experienced designers and managers involved in AHS design and also manage several of the products the case company is developing. The following positive feedbacks are obtained related to SBCE IR:

- SBCE IR will help the case company to be proactive to plan ahead projects for new products.
- SBCE IR will help the company to structure the innovation process.
- SBCE IR will help the company to build innovation roadmap for projects on new products from bottom-up basis.
- SBCE IR is based on contradictions and this helps the company to overcome them and offer innovative product and technologies.
- SBCE IR reduces the extensive nature of conducting SBCE process, and will enable the company to focus on important improvement areas.
- SBCE IR is effective in structuring the evaluation of requirements for customer importance.
- SBCE IR is effective in evaluating competitive products.
- SBCE IR has the potential to improve the quantity, quality, novelty and variety of new ideas to be generated during the exploration phase SBCE process.
- SBCE IR is not difficult to build.
- SBCE IR is scalable and applicable to different kinds of products or modules.

The experts also identified limitations related to building and using the SBCE IR methodology. These limitations are summarized as follows:

- SBCE IR should be considered as a rough-cut methodology to identify areas for SBCE implementation. More detail investigation should be considered based on company's strategy on which contradictions should be targeted.
- SBCE IR becomes unstable if the list of customer requirements identified in step 1 of the methodology changes frequently by customers. Close collaborations and interactions are needed to avoid this problem.

- SBCE IR doesn't consider the different type of customers the company is targeting. Thus, difference customers might have different judgment of importance for a requirement. Take must be taken to balance the needs of different customer types.
- Taking competitors analyses might mislead designers to make only small improvements just to beat competitions rather than making great and high level innovation.
- Personal experience and imagination of designers are necessary to make SBCE IR enhance quality and novelty of ideas generated.
- Building SBCE IR is time consuming in particular for big, complex and highly new products.
- SBCE needs skills and training such as SBCE training, TRIZ training. Moreover, building SBCE needs expertise in having a holistic vision of product development process from the customer needs collection phase to the whole lifecycle of a product.

There are several potential future researches to improve the SBCE IR methodology. The following future research questions are proposed for future researches:

- How to align SBCE IR with company's strategy for projects on new products and portfolio management process?
- How to improve SBCE IR to consider different types or levels of customers? And what are the impacts of having different customer types in solving contradictions using SBCE process?
- How to build SBCE IR for product modules or platforms? And what are the benefits in terms of stabilizing the SBCE IR and reducing the time it takes to build SBCE IR?
- How to simplify SBCE IR for small projects (new product with small improvements from the current design)? And, How to automate the SBCE IR for complex products to make the analyses involved in SBCE IR less time consuming?
- How to distribute contradictions to different development organizations? (For example, development organization in the case company is divided into two: product development, focusing on designing products upon customer request; and technology centers, which aim to develop new technologies and feed knowledge to the product development organization). Therefore, which contradictions to assign to which development organization is an open issue.

## 8 THESIS SUMMARY AND FINAL CONCLUSIONS

The underlying idea of SBCE is not new. In fact, it has been more than a decade since it has appeared in literature. Although, the original proponents formalize and name it as SBCE, the principles are well-known to many inventors and experimenters well before Toyota. The Wright brothers who invented the first flying machine once said “...if some method could be found by which it would be possible to practice by the hour instead of by the second there would be hope of advancing the solution of a very difficult problem...and without any serious danger” (Kennedy 2010). This notion of focusing on experimenting, exploring, testing of sets has been the norm to several inventors who contributed to the industrial revolution and humanity. Designers in any company face several unpredictable and uncertain conditions in early design phases. In



these conditions, the principles of SBCE make much more sense than PBCE. Moreover, design is a process where problems are discovered, solved and knowledge is created. However, in the current industrial context, PD has become more formal and structured process rather than a knowledge creation factory. Developers start to focus on meeting deadlines and milestones. Experimentation, testing, and consideration of sets started to be given less attention or less practiced. This trend, however, result many companies to suffer on PD performances. Lack of innovation, project delays, cost overruns, poor qualities, knowledge wastes, and poor learning capabilities are among the challenges that industries are facing at the moment. SBCE, if integrated well, will be significantly contributes to alleviate the challenges. SBCE contributes to revolutionize companies to be a true learning organization. Through its principles, SBCE will guide designers and managers to orient themselves for the creation of high value products and strive to create usable knowledge in PD.

The conception of this thesis was born by asking if SBCE really be a practice that industries can adopt it with full consciousness. After several personal experiences, what lies beneath the industrial practice in early phase of design is all about consciousness. Designers are well aware of the fact that PBCE has many drawbacks. In fact, there are several elements of SBCE that are practiced in many organizations, such as the

consideration of alternative concepts, knowledge front-loading at early phase of design, test before commitment, communication, collaborations and so on. Nevertheless, if SBCE is not acknowledged by industries as a standard process to be followed, the potentials of SBCE cannot be fully utilized. Having said this, the existing literature of SBCE has not been well contextualized to be readily adopted by many industries.

Irrespective of its popularity in academic discussions or consultants ads, industries have little knowledge and guidelines on how to execute the principles and the necessary capabilities needed are not well articulated in existing literature. As a result, it has been observed that there is low awareness level in many of the industries interviewed in this thesis (as other researches showed). SBCE is a promising paradigm; many believe can benefit the industries in several ways. Nevertheless, still its understanding in practice is at the fledging state. Moreover, practical methodologies are required to make SBCE principles and process pragmatic.

In conclusion, this thesis advances the existing academic and practical gaps in three main directions. A first advancement is related to the integrated framework of SBCE's enablers discussed in chapter 4. A first methodological contribution is the development of SBCE serious game which is discussed in chapter 6 (PART I). Moreover, thanks to the introduction and validation of the SBCE serious game in the case industry, several lessons are obtained that will be insightful for both practice and theory. The second methodological contribution is the related to SBCE IR which is introduced and validated in chapter 7 (PART II). This methodology will have significant contributions to guide designers on which improvement areas SBCE should be applied. Hereafter, each contribution is analyzed and summarized again in brief:

## **8.1 Integrate framework of SBCE's enablers and its implications for practice and theory**

The proposed integrated SBCE framework is composed of the pillars of SBCE, its principles and enablers. Extensive literature review has been conducted to build the framework. The review includes literature from product design, knowledge management, tools, methods, technologies, and concurrent Engineering bodies of knowledge in product development. The SBCE framework can significantly contribute to both the industry and the theory. For the industry, the framework will show what enablers SBCE demands to be adopted in practice to effectively execute the principles and the process. Companies can investigate their practices and capabilities to assess their PD for SBCE adoption. For the literature, the framework will enrich the arguments presented about the roles of SBCE. Several concurrent engineering literatures portray SBCE as a mere consideration of multiple alternatives in parallel (e.g. Terwarch, et al. 2002; Bogus 2006). These literatures further advice to limit the number of alternatives to consider when the value creating in doing so is less than the cost. However, the value of SBCE is much richer and often difficult to quantify (e.g. learning/

knowledge, innovation). Moreover, there is a lack of an integrated framework showing organizational changes required to put the SBCE's principles into practical world. Therefore, if the enablers are included in the discussion about the role of SBCE in PD, the existing narrowed view of SBCE will have the possibility to expand and enriched. Furthermore, future researchers can focus on studying the impact of the enablers in the effectiveness of SBCE and devising strategies based on the framework to measure maturity levels of PD organizations in adopting the enablers to make SBCE more effective.

## **8.2 SBCE serious game and its implications for practice and theory**

The SBCE serious game is designed to bring a hand-on experience to practitioners on how execute the principles and process of SBCE, in an engaging manner. Some of enablers of SBCE are embedded in the game. Enablers such as tool, communication, involvement, knowledge capturing and using are designed in the game to educate players about their roles in SBCE. The game is used for two purposes. First to introduce SBCE to players and second to measure the learning outcomes of the game play. Measuring the learning outcomes of the game enable to derive theoretical and practical insights about the understanding, applicability, and steps of SBCE implementation in practice. Based on Garris model (Garris, et al. 2002) for measuring the learning outcomes of games, three learning classifications are measured in SBCE game (declarative, procedural and strategic). Moreover, questionnaire based on Likert five scales model has been developed to measure the learning outcomes. The game has been played by more than 60 designers and project managers who work in one company, which develops products for HVACR (Heating, Ventilation, Air-Conditioning and Refrigeration) markets. For measuring the learning outcomes of the play, appropriate descriptive and inferential statistics are used. From the measurement, it has been possible to derive several insights related to the advantages, hurdles, and implementation challenges of applying SBCE in this particular case company. The results obtained from this company are summarized in Table 6.14. Moreover, the lesson learned from the case which can highlight important significances for practice and theory are recapped as follows:

- The SBCE serious game is effective to educate practitioners, increase their awareness level about SBCE and convince them to adopt principles and enablers of SBCE in their design practice. Moreover, the game has been effective in helping practitioners on how to use SBCE's principles and tools in practice.
- Industrial practitioners assert that, SBCE has significant potential to improve PD performances even for smaller or medium sized companies. Tools such as tradeoff curves, checklists, and limit curves are perceived as key enablers to effectively integrate stakeholders in SBCE process (e.g.



- customers and testing department as downstream function). Moreover, the tools are perceived to be effective to evaluate sets for compatibility issues and understand feasibilities of alternatives.
- In order to effectively deploy SBCE, experience of designers and managers is found to be important. Coaching and mentoring of novice engineers from highly experienced ones help less experienced designers to conduct SBCE. Furthermore, SBCE enablers such as tools (tradeoff curves, checklists, and limit curves) are very important to capture and visually depict performance information about sets to further transfer to less experienced designers.
  - Project or product development managers should work to obtain organizational wide buy-in before starting a real implementation of SBCE. The game result shows that, managers and technical designers have significant differences in understanding SBCE and perceiving its benefits. Managers have high expectations from implementing SBCE in terms of performance improvements and success. However, without the support of technical designers, the success of SBCE might fall in jeopardy. Therefore, implementation of SBCE should be taken as a change process where managers convince, support and involve technical personnel in the change process.
  - Industrial players assert that using tradeoffs in practice limit innovation. In the SBCE game, tradeoffs have been used to explore alternative subsystems and facilitate communication between teams. However, accepting tradeoffs or compromises might limit the potential of SBCE to enhance innovation (in terms of discovering out of the box solutions). This, however, can be overcome by integrating SBCE with established theories of innovation such as TRIZ (SBCE IR has been conceived based on this inkling from practitioners).
  - Some of the enablers (tradeoffs and limit curves) are difficult or challenging to generate in practice. In companies where there are limitations in employing technologies for prototyping and simulations, generating these SBCE enablers might be challenging. Moreover, modeling and generating of tradeoff curves are not seemingly simple in practice because performance parameters are difficult to relate. Similarly, testing alternative solutions to their constraints need extensive time in preparing and evaluating alternative prototypes.
  - Set based communication where designers communicate with internal teams or external suppliers based on alternatives, rough/vague/unfinished information is perceived not critical and unpractical in this particular case company. Four practical reasons can be attributed to this result from the game. First, new product development projects involve few designers and managers (sometime one or two). In this situation, SBCE tools such as checklists are not that critical to

use. A notice to take is the origin of SBCE. Principles such as set based communication are originated from big automakers like Toyota where there are several subsystems teams involved in a vehicle development which are dispersed across the globe. In this situation, SBCE should be facilitated by checklists as communication mechanism between team members to evaluate their respective sets of alternatives. In Carel Industries, where there are few and collocated team members involved, verbal communication might be sufficient to communicate about sets of alternatives. The second reason might be related to the complexity of products developed in this particular company (HVACR) where there are few subsystems to develop in a particular project. Again, in this situation, set based communication might not be as critical as it would be in developing very complex products in automotive or aerospace industries. The third reason is related to the impact of set based communication when it comes to external suppliers. In its original sense, SBCE principle of set based communication is formed between Toyota and its partnering suppliers. Toyota asks for its suppliers to explore multiple solutions for a vehicle [e.g. up to 10-50 prototypes of exhaustive systems (Sobek and Ward 1996)]. Toyota does this to understand the tradeoffs between the performances of alternatives. That means Toyota obtain knowledge about alternatives and can plan its development of cars accordingly. Such kinds of opportunities are rare in many other industries in particular for small and medium sized ones. Small and medium companies have difficulties to create strong relationships between partners to do extensive prototyping in their behalves. As a result, such companies will have little opportunities to build knowledge about alternatives and between their suppliers. The fourth reason is related to the well-known cliché about the price based relationships between companies and their suppliers within the Western business philosophy. The original inception of set based communication is from the Japanese companies as of Toyota, Honda, etc. Even these Japanese companies conduct set based communication with their partners (not common suppliers). Set based communication leave rooms for suppliers to abuse the relationships to offer bad performing alternatives just to make more profit (Liker, et al. 1996). In this context, designers and managers of Western companies want to make point based communication (i.e. communicating based on a single alternative or defined and precise information) to avoid the risks.

- The final lesson learned obtained from the game play can be summed as ‘SBCE is a journey’. In order to improve performances using SBCE principles, the understanding, adoption of SBCE enablers are important. Developing tools, involving stakeholders, and effective communication should be in place to build knowledge. Then, performance benefits can be shown as a result and companies can successful implement SBCE and develop products in a knowledge based

environment. But, it needs efforts and investments to effectively build an organization that effectively manage and share knowledge to develop products. Therefore, SBCE should be taken as a process and as a journey where knowledge is systematically captured as a long term strategy.

In sum, the game can be used by any company who wants to train its designers and managers. Moreover, it can be used to identify the advantages, difficulties and applicability of adopting SBCE process in a particular industrial context before implementing it in real PD process, and drive strategic roadmap to begin SBCE implementation program.

More researches can also be done on the game design and on the validation sides. To improve the game design, other enablers of SBCE which are not considered in the current version can be embedded in the game. These enablers for example are related to organizational aspects, people competences, chief engineering system and so on (refer to in chapter 4 to the details of SBCE enablers). From the measurement and validation side, researchers should be pursued to experiment playing the game in different industrial contexts (e.g. SMEs, big OEMs, small suppliers, simple products, complex products etc.) and identify the differences in the results. Moreover, robust and externally valid results can be obtained by playing and measuring the game in different industrial contexts.

### **8.3 SBCE Innovation Roadmap (SBCE IR) and implications for practice and theory**

At a product level, the application of SBCE is not a random initiative. Designers should know where SBCE can bring significant improvements. Otherwise, implementation failures will likely to occur. The extensive nature of SBCE process requires the systematic methodology which is developed in this thesis. The methodology is called SBCE innovation roadmap (SBCE IR). This roadmap is used as a guideline for designers to prioritize product subsystems for SBCE implementation. Before building the methodology, key criteria and assumptions are identified such as: (a) the process of overcoming contradictions will follow SBCE process, (b) areas of improvements should be valuable for customers, (c) areas of improvements should give competitive advantages, and (d) areas of improvements should be achievable with respect to the resources available. Using the criteria and assumptions, the six steps SBCE IR methodology has been developed. Moreover, the steps are built on prevalent tools and methods available in literature. The steps include, (1) Identification of customer requirements & assigning importance, (2) Assess competitors' products for each customer requirements & set targets, (3) Identify system contradictions, (4) Identify casual contradictions, (5) Derive rules to select contradictions, and (6) Map contradiction to products' subsystems or components or in general to design factors. Contradictions are used to identify knowledge gaps that have been unsolved in a product system. However, each contradiction will not lead to same level of innovation, so

rules have been developed to prioritize them. The rules are based on customer information, competitors' analyses, technology trends, and causal relations between contradictions. Using the above steps, SBCE innovation roadmap can be developed. Using it, designers can make prioritization of contradictions to pursue SBCE process.

The SBCE IR methodology is validated in AHS (Adiabatic Humidification System) case study. In order to test and validate the methodology, the SBCE IR is built for AHS. Data for the steps are collected from the experts of AHS. Next, using the roadmap of AHS, designers choose a subsystem called Rack. The contradiction related to this has been 'non-VDI requirement'. TRIZ principle of separation is agreed by the company to be used. That is, two Rack versions will be offered to clients who require VDI6022 and for those who don't require the hygienic requirement. Then, exploration of alternative Rack concepts was generated, tested and merged for non-VDI Rack (i.e. conducting SBCE process). From the experiment, experts anticipated an estimated of 30% cost reduction in comparison of the current design (VDI compliant Rack). The cost advantages were obtained by looking for alternatives materials, removing non-value adding components, and reducing unnecessary manufacturing and assembly operations.

Then, pros and cons (e.g. advantages compared to existing methods used in the company, applicability, effectiveness, limitations, etc.) of the SBCE IR have been assessed by conducting interviews with designers and project managers involved in the case study for AHS. An open questionnaire is provided to evaluate the advantages, limitations and applicability of SBCE IR in the company. Interviews are made with four experts in the company who are well experienced and have technical, managerial and market competences. These experts have been extensively involved collecting data and building SBCE IR for case product (AHS). The results of the interview are summarized in Table 7.13 and discussed in detail in sections (7.3.3.1, 7.3.3.2 and 7.3.3.3).

In summary, the SBCE IR has been effective to meet the objective set for it. The SBCE IR as assessed by the AHS experts help/ will help them to be proactive to plan ahead projects for new products, structure the innovation process, build innovation roadmap for projects on new products from bottom-up (from designers/ technical level to management level, see Figure 7.13) basis, overcome contradictions and thereby start innovating, reduce the extensive nature of conducting SBCE process and will enable the company to focus on important improvement areas, structure the evaluation of requirements for customer importance (customer value focus) and improve the quantity, quality, novelty and variety of new ideas to be generated during the exploration phase SBCE process.

On the other hand, limitations are identified related to building and using the SBCE methodology. These are: SBCE IR should be considered as a rough-cut methodology to identify areas for SBCE implementation, where more detail investigation can be considered based on company's strategy; SBCE IR becomes unstable

if the list of customer requirements changes frequently by customers, to avoid this close collaboration and frequent visit at customer sites are suggested; SBCE IR doesn't consider the different type of customers the company is targeting, this is related to the consideration of customer layers and the aggregation of importance for a requirement; personal experience and imagination of designers are necessary to make SBCE IR enhance quality and novelty of ideas generated; building SBCE IR is time consuming in particular for big, complex and highly new products; and skills and training are needed related to SBCE's principles, TRIZ principles, PD process knowledge across the whole lifecycle of a product.

Future researches can target to improve the limitations of the SBCE IR methodology. For example, integrating SBCE IR with company's strategy, redesigning SBCE IR steps to consider multiple types of customers, redesigning SBCE IR methodology for modules or platforms, simplifying the SBCE IR steps for small projects which are based on incremental improvements, automate the steps of the methodology and devising strategies on how to distribute contradictions to different organizations (e.g. which contradictions to assign to development process, and which to assign to R&D organization?).

## **8.4 Integrated framework of SBCE's enablers, SBCE serious game and SBCE IR – Synergies and future perspectives**

The above contributions are highly interrelated pieces of works. From industrial implementation perspective, the SBCE serious game helps companies to educate and introduce the concept of SBCE at a glance. Then, managers can meter the applicability of SBCE in their particular company. Before the development of SBCE IR in this thesis, the feedback from the game results has been educative. The limitation of concentrating on tradeoffs and the extensive nature of applying the SBCE's principles give hints on the criteria to build the SBCE IR. Similarly, industries can play the game and can plan for a methodology that can suit them to begin SBCE implementation journey. This shows the synergies between the SBCE serious game and the innovation roadmap methodology. The SBCE IR can be used as an independent methodology to identify and prioritize contradictions and to overcome them using the SBCE principles. Before implementing SBCE IR, however, the game can help to educate players on what the SBCE principles mean and how to practically implement them using a simplified airplane. Referring to (Table 7.13), one of the skills required to effectively build an innovation roadmap is knowledge about SBCE principles, therefore, the game has a synergies in this aspect with SBCE IR.

Looking at the integrated framework of SBCE enablers, the SBCE serious game is designed by embedding some of the enablers. Obviously, it is not easy to embed all the enablers of SBCE into a game, nonetheless future researchers might study on how to embed some of the enablers which are not considered in SBCE

game's current version. Therefore, there are potentials for future researches by looking the enablers and the game design.

Future researches can also look at the synergies between enablers of SBCE and SBCE IR methodology. The current version is designed by integrating some of the SBCE enablers into the SBCE IR's steps. QFD, TRIZ and AHP have been mentioned as enablers of SBCE. These tools and methods are used in SBCE IR. Future researches might look at other enablers such as Value Engineering (VE), Axiomatic Design (AD) and etc. to improve the methodology or solve different kinds of problems or challenges related to SBCE application in industry.

A final research perspective will be to see SBCE as a journey, and integrate the SBCE serious game, SBCE IR and the framework of SBCE enablers. Using the game, a company can train designers the principles and enablers of SBCE. Then, building SBCE IR will be the next step. Taking specific products, a company can identify and prioritize areas which are critical to be addressed using SBCE. Finally, taking the enablers from the integrated SBCE framework, the necessary organization capabilities and changes can be assessed and implemented on the selected part of the organization. However, integrating the three will demand future research.

I hope researchers will find these as important endeavors and will have exciting and challenging time ahead!!

# PHD CANDIDATE PUBLICATIONS

## *Journals*

1. E. Kerga, M. Taisch, S. Terzi, M. Rossi (2013) A Serious Game for Introducing Set-Based Concurrent Engineering in Industrial Practices. *Journal of Design Research (JDR)*, *under review*.
2. E. Kerga, M. Taisch, S. Terzi (2013) Set-Based Concurrent Engineering Innovation Roadmap (SBCE IR): A case on Adiabatic Humidification System. *Int. Journal of Design Creativity and Innovation (IJDCI)*, *under review*
3. M. Rossi, E. Kerga, M. Taisch, S. Terzi (2012) Lean Product Development: a Learning Methodology for Waste Identification and Prioritization. *Int. Journal of Product Development*, *under review*
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## *International Conferences*

5. E. Kerga, M. Taisch, S. Terzi (2010) Set Based Engineering and Eco-efficient design selection at conceptual phase of product design and development process. In: *Proc. of International Conference on Advances in Production Management Systems (APMS) Competitive and Sustainable manufacturing, products and services, Cernobbio (Italy), October 11-13, 2010*, pp.4-18. ISBN: 9788864930053
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# APPENDIX

## Appendix A1: Semi-structured questionnaire used to assess the practices of SBCE in industries

The questionnaire is developed by University of Cranfield and the purpose has been to investigate lean product development practices across industrial partners under the EU funded project LeanPPD ([www.leanppd.eu](http://www.leanppd.eu)). The questionnaire is reused in this thesis to assess the industrial practices of SBCE principles and enablers across industries in Italy. There were 39 questions in the questionnaire, however, here only those which are used in chapter 5, section 5.2.2.




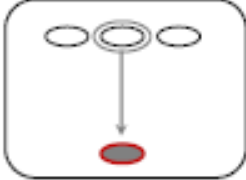
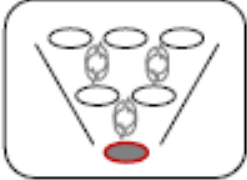
  	
<b>Semi Structured Questionnaire for LeanPPD Field Study</b>	
<i>Grant Agreement number:</i>	NMP-2008- 214090
<i>Project acronym:</i>	LeanPPD
<i>Project title:</i>	Lean Product and Process Development
<i>Funding Scheme:</i>	Large Collaborative Project
<i>Date of latest version of Annex I against which the assessment will be made:</i>	20.02.2009
<i>Academic Supervisor names, title and organisation:</i>	Dr. Ahmed Al-Ashaab & Dr Essam Shehab Cranfield University
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<i>E-mail:</i>	<a href="mailto:a.al-ashaab@cranfield.ac.uk">a.al-ashaab@cranfield.ac.uk</a>
<i>Project website address:</i>	<a href="http://www.leanppd.eu">www.leanppd.eu</a> , <a href="http://www.leanppd.org">www.leanppd.org</a> , <a href="http://www.leanppd.net">www.leanppd.net</a>
<i>Start date of the project:</i>	01.02.2009
<i>Duration:</i>	48 months
<i>Responsible of the Document</i>	Cranfield University Team <a href="mailto:a.al-ashaab@cranfield.ac.uk">a.al-ashaab@cranfield.ac.uk</a>
<i>Due date of deliverable</i>	n/a
<i>Document Ref.:</i>	<i>Questionnaire for field study</i>
<i>Version:</i>	1
<i>Issue Date:</i>	29/February/2010

Figure A1: Introduction and ownership of the Field study questionnaire.


2.2. From the diagrams below can you indicate what method(s) of product development do you currently follow and rate its effectiveness?



Concurrent Eng



Set-Based Concurrent Eng



Sequential Manner

Method	Frequency of use			Effectiveness		
	Never	Some times	Always	Not Effective	Somewhat Effective	Very Effective
Concurrent Eng	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Set-based Concurrent Eng	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Sequential Manner	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure A2: PD models practices and its effectiveness.

1.5. How do you select the design solution that will be developed? (select one option)

Options	
<input type="radio"/>	We only produce one design solution for each product
<input type="radio"/>	We identify multiple solutions, and select the one that most closely matches the design specification
<input type="radio"/>	We identify multiple solutions, and select the solution that has the lowest development costs
<input type="radio"/>	We design multiple solutions for each product/ component, and rule them out as more information becomes available (due to prototyping, testing, integration etc.)

Figure A3: PD models practices and its effectiveness.

5.3. What challenges do you face with regards to knowledge capture and representation? (you may select more than one option)

Options	
<input type="checkbox"/>	Often very time-consuming
<input type="checkbox"/>	Incompatibility of knowledge formats between different software
<input type="checkbox"/>	Unnecessary knowledge capture and over-crowded documents/figures/posters/databases etc.
<input type="checkbox"/>	Designers find it difficult to extract knowledge from previous projects

Figure A4: PD models practices and its effectiveness.

3.2. Do you have formal initiatives or software(s) for capturing previous projects in a common database to provide a source of information and knowledge to support new product development? (Select one each)

Initiatives	Ratings				
	No initiative & Not interested	Desired	Initiated	In Progress	Fully Established
Lessons Learned	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
CAD Files	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
CAE Files	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Test Data	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
BOM	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Technical Issues	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Cost Data	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Product Specifications	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Engineering Requirements	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

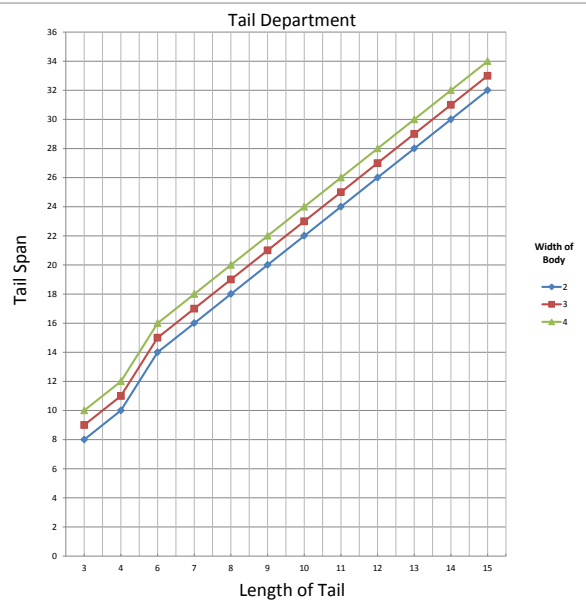
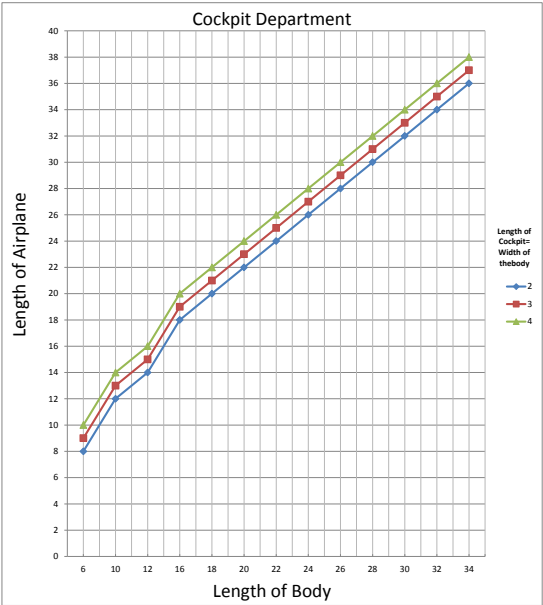
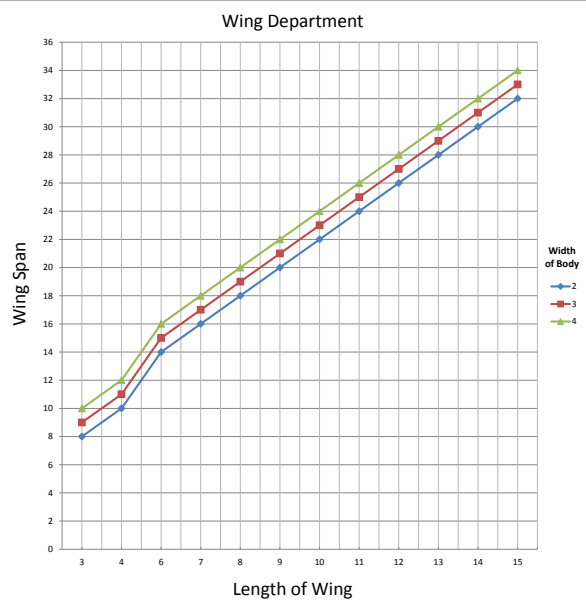
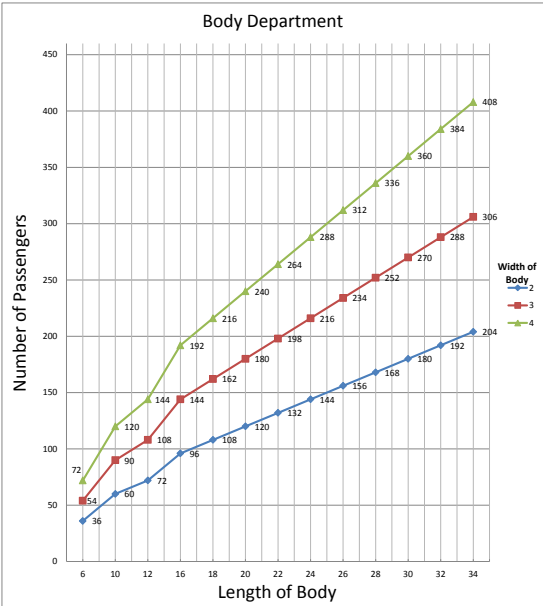
3.3. Currently what are the implemented mechanisms to capture knowledge in your organisation and how efficient do you assess them? (Select one each)

Mechanisms	Usage			Effectiveness		
	Never	Some times	Always	Not Effective	Some what Effective	Very Effective
Verbal communication	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Questionnaires	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Document Templates	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Web-Blogs/ Notice Boards	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
<input type="checkbox"/> We have no implemented mechanisms to capture knowledge in our organisation						

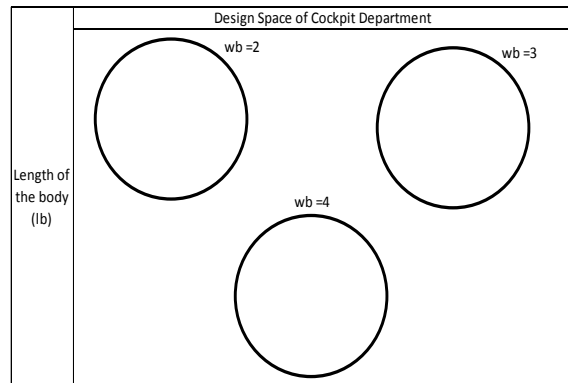
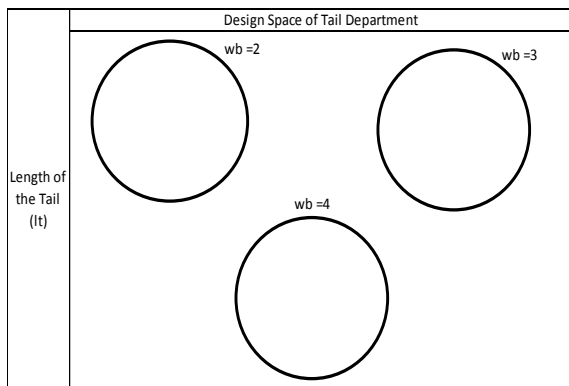
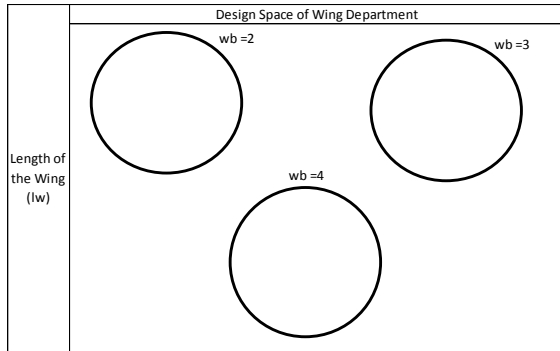
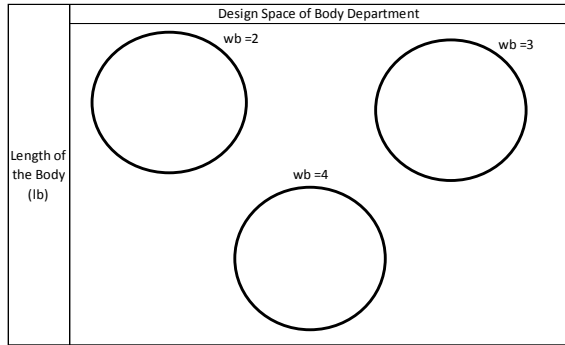
Figure A5: Knowledge capturing mechanisms, usage and effectiveness.

# Appendix B

## B1: Trade-offs curves for Body, Wing, Cockpit, and Tail departments

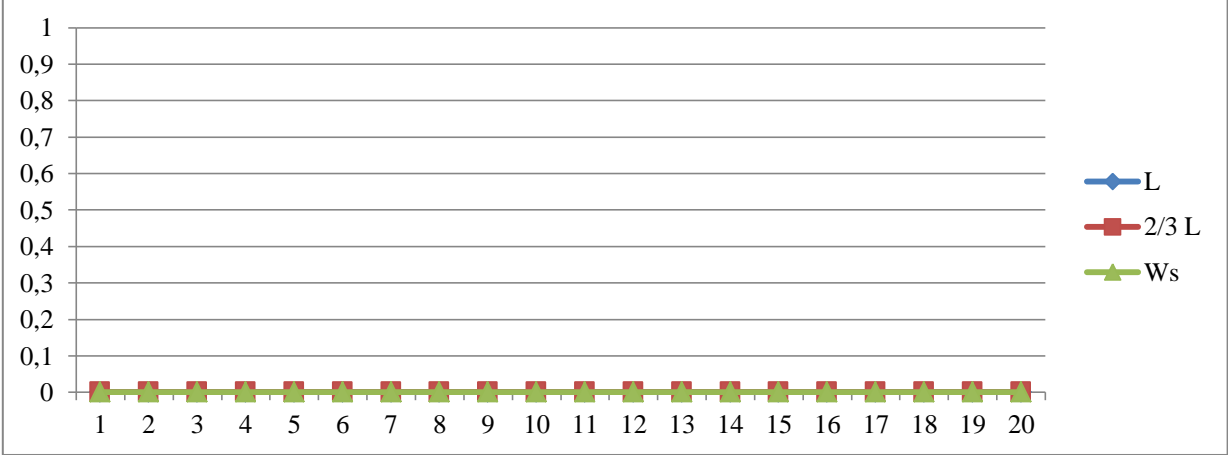
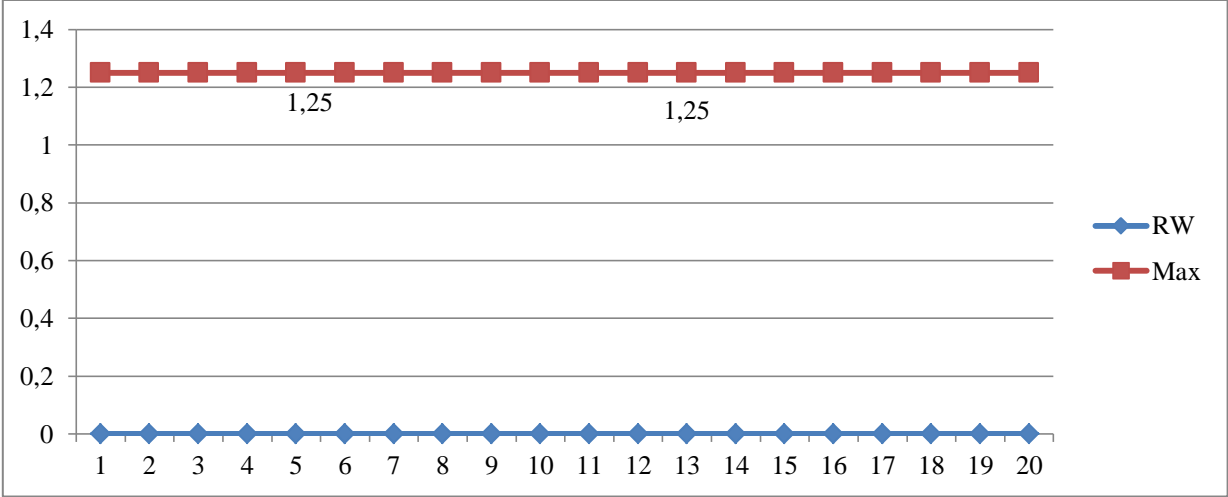
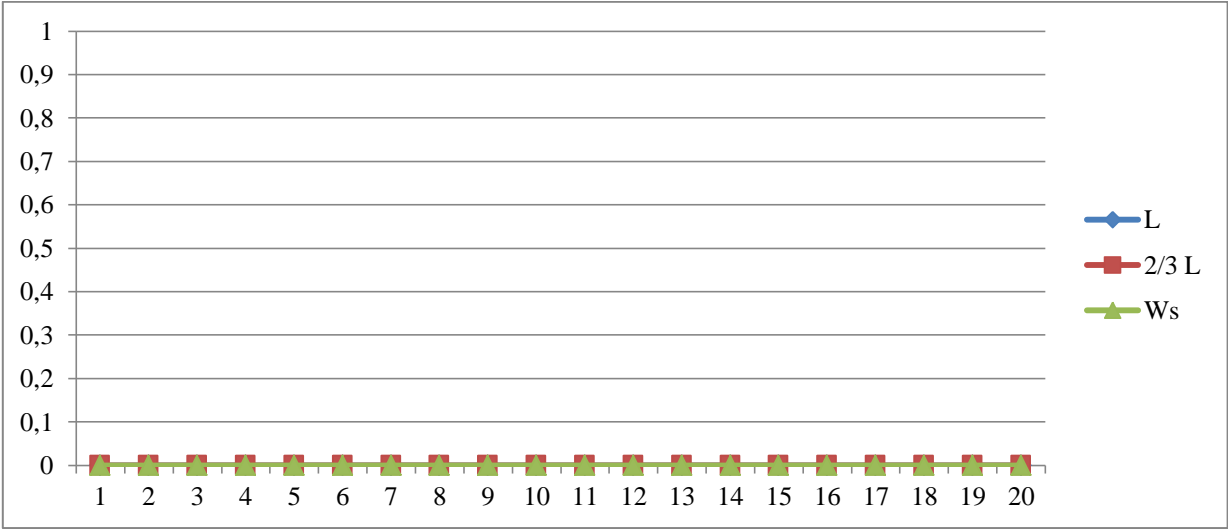


## B2: Checklists for Body, Wing, Cockpit, and Tail departments

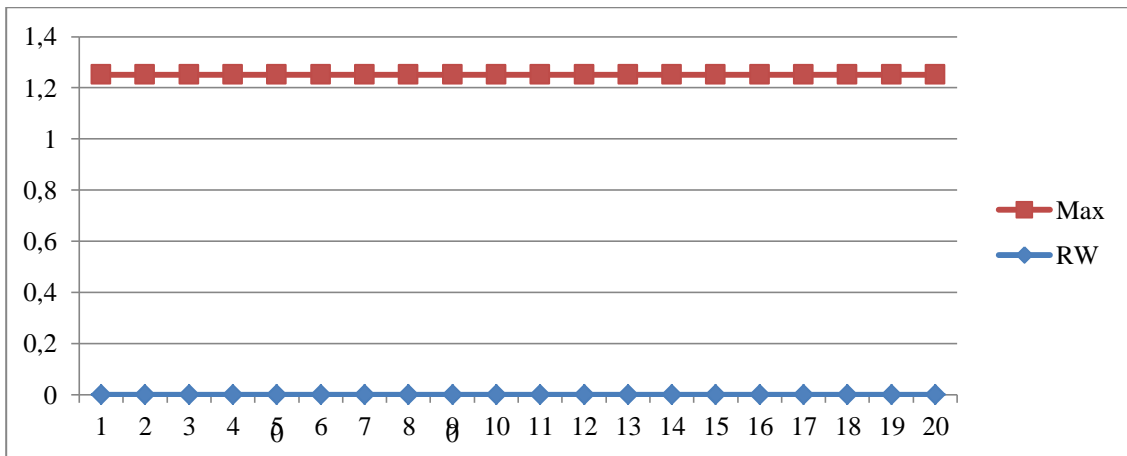
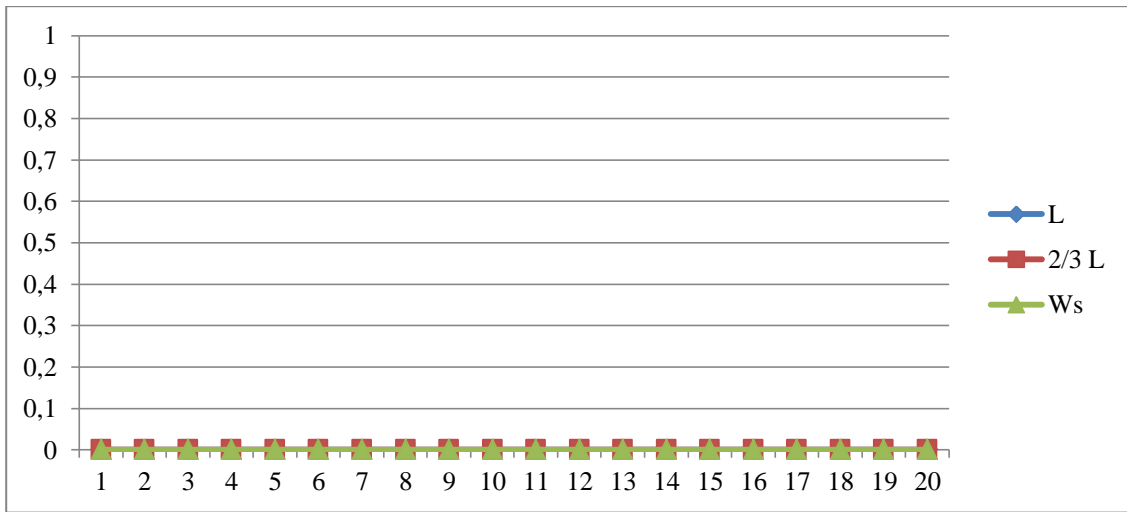
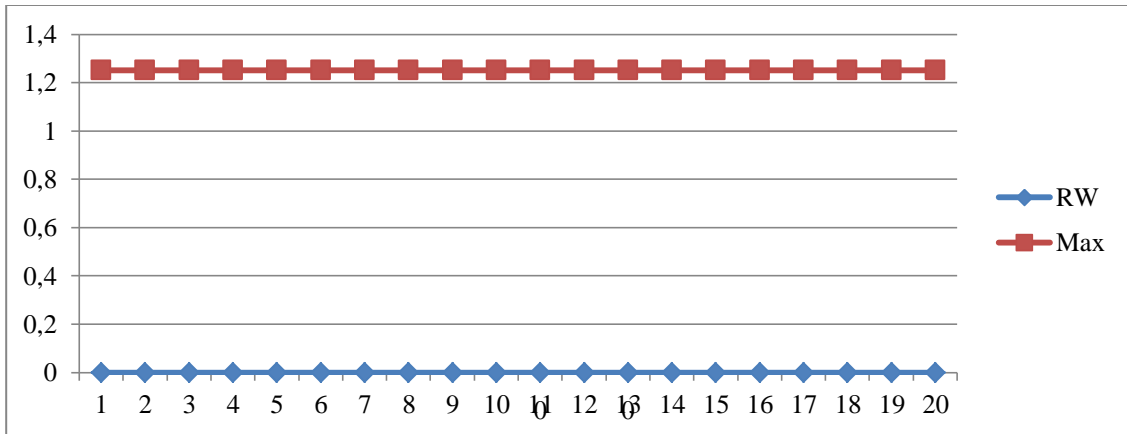


Possible Design Alternatives			
Dimensions	wb		
	2	3	4
lb			
lw			
lt			

B3: Limit curves for technical feasibilities







**Appendix C1: Questionnaire for measuring the learning outcomes of the SBCE serious game**

**Questionnaire**

This questionnaire is prepared to understand the learning outcomes of playing the SBCE game. Moreover, the results of the questionnaire help us to improve the design of the game in order to achieve better learning outcomes. Please, provide us your honest opinion about the listed questions and contribute for a better SBCE game.

**I. Background information**

Your working position (Circle that fits you)	1. Product manager/Project leader/other management position 2. Change agent/Lean Manager etc. 3. Mechanical part designer 4. Electrical part designer 5. Thermal part designer 6. IT part designer and/or debugger 7. Engineering student 8. Engineering management student 9. Consultant services 10. Other, please specify.....
Age	
Approximate years of design and product development experience	
Gender (Circle that fits you)	1. Female 2. Male

**II. SBCE game questions**

Strongly disagree (1), Disagree (2), Neither agree nor disagree (3), Agree (4), Strongly disagree (5) .

(Circle your evaluation)	Strongly disagree				Strongly agree
1. Playing the SBCE game is worthwhile to your product development process	1	2	3	4	5
2. Playing SBCE game will improve your problem solving ability in new product design	1	2	3	4	5

3. The game help you to understand the challenge of designing a product that fully satisfy customer requirements	1	2	3	4	5
4. The game help you to understand the challenge of designing a product that fully satisfy testing requirements	1	2	3	4	5
5. The game help you to clearly understand the problem of communication within a product development team	1	2	3	4	5
6. The game let you understand how SBCE works along with its enabling tools	1	2	3	4	5
7. Playing SBCE game make me believe that SBCE is a better design process than the one we followed in the company	1	2	3	4	5
8. The game help me to understand how to explore alternative design solutions using the tools played in the game	1	2	3	4	5
9. The game help me to design sets of solutions rather than one solution	1	2	3	4	5
10. The game help me to communicate about set with my team than one solution	1	2	3	4	5
11. The game help me to effectively understand the usage of limit-curves	1	2	3	4	5
12. The game gives me an insight how to communicate with my teams about sets of design solutions					
13. It is possible to develop some limit-curves (as shown in the game) for a product I a am designing but it is not easy	1	2	3	4	5
14. It is possible to develop some limit-curves (as shown in the game) for a product I a am designing and it is easy	1	2	3	4	5
15. It is not possible at all to generate limit-curves as shown in the game	1	2	3	4	5
16. The game gives me insights about the importance of capturing design knowledge in a in the form of tradeoff and limit curves	1	2	3	4	5
17. The game gives me insights on how to use tradeoff and limit curves in my current and future design problem	1	2	3	4	5
18. It is possible to develop a mechanism for communicating set of solutions with in a design team in our company	1	2	3	4	5
19. Playing the game gives me a better insight how to	1	2	3	4	5

communicate in my design practice					
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In your opinion which of the following advantages of SBCE is evident by playing SBCE game	Strongly disagree				Strongly agree
1. Reduction of product and process cost, by reducing rework and penalty cost	1	2	3	4	5
2. Reduction of development time	1	2	3	4	5
3. Improve innovation potential	1	2	3	4	5
4. Better communication within a team	1	2	3	4	5
5. Avoid design risks (risk is defined as the possibility of not arriving into optimal product that satisfy internal and external customer)	1	2	3	4	5
6. Improve product quality	1	2	3	4	5
7. Facilitate learning about alternative design solutions	1	2	3	4	5

### III. Practical questions

From your experience please give at least one example where a SBCE model can be applied. It could be at component level, module level or full product level.

From your experience please give at least one example where a tradeoff curves can be generated and reused for exploring alternative design solutions. It could be at component level, module level or full product level.

From your experience please give at least one example where a limit curves can be generated and reused for testing alternative design solutions. It could be at component level, module level or full product level.

Please provide us any comment that you think is important from practical implementation perspective. That is, what potential problem you think will inhibit SBCE to be effectively implemented in your design practice.
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Please provide us any comment that you think is important to improve the SBCE game.
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